

Agriculture in a Changing Climate: Impacts and Adaptation

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CONTENTS

Executive Summary	429	13.7. Regional Summary: Relative Vulnerability	446
13.1. Introduction	431	13.8. Global Agricultural Issues and Assessments	449
13.2. Climatic Effects on Crop Plants	431	13.8.1. The Current and Future Agricultural System	449
13.2.1. Elevated CO ₂ and Crops	431	13.8.1.1. Demand Growth	450
13.2.2. Temperature, Moisture, and Other Variables	432	13.8.1.2. Land Quantity and Quality	450
13.3. Soil Changes and Agricultural Practices	434	13.8.1.3. Water Supply and Irrigation	450
13.4. Weeds, Insects, and Diseases	435	13.8.1.4. Future Yield Growth	451
13.4.1. Weeds	435	13.8.1.5. Future Economic Development	451
13.4.2. Insect Activity and Distribution	435	13.8.2. Global Climate Impact Studies	451
13.4.3. Plant Diseases	437	13.9. Adaptation	452
13.5. Animal Agriculture	437	13.9.1. The Technological Potential to Adapt	453
13.6. Regional Climate Impacts: Studies and Issues	438	13.9.2. The Socioeconomic Capability to Adapt	453
13.6.1. Africa and the Middle East	438	13.10. Research Needs	455
13.6.2. South and Southeast Asia	439	Acknowledgments	455
13.6.3. East Asia	440	References	455
13.6.4. Oceania and Pacific Island Countries	441		
13.6.5. Areas of the Former USSR	442		
13.6.6. Latin America	443		
13.6.7. Western Europe	444		
13.6.8. USA and Canada	444		

EXECUTIVE SUMMARY

Substantial research progress has been made on the impacts of climate change on agriculture since the 1990 IPCC assessment, with new studies for different sites and countries covering many areas of the world. New studies also have been conducted that integrate site, country, and regional impacts to provide information about how global agricultural production and consumption may be affected. On the whole, these studies support the evidence presented in the first IPCC assessment that global agricultural production can be maintained relative to baseline production in the face of climate changes likely to occur over the next century (i.e., in the range of 1 to 4.5°C) but that regional effects will vary widely. Major uncertainties result from the lack of reliable geographic resolution in future climate predictions, difficulties in integrating and scaling-up basic physiologic responses and relationships, and difficulty in estimating farm sector response and adaptation to changing climate as it varies across the world. Thus, while there will be winners and losers stemming from climate impacts on agricultural production, it is not possible to distinguish reliably and precisely those areas that will benefit and those that will lose.

Major conclusions of the assessment cover four areas: (1) The direct and indirect effects of changes in climate and atmospheric constituents on crop yield, soils, agricultural pests, and livestock; (2) estimates of yield and production changes for specific localities, countries, and the world, based on studies that integrate multiple direct and indirect effects; (3) the conditions that determine vulnerability and areas and populations that are relatively more vulnerable to adverse changes; and (4) adaptation potential.

Direct and Indirect Effects

Experimental results, detailed modeling of basic processes, and knowledge of physical and biological processes provide basic understanding of direct and indirect effects of climate on agricultural production:

- The results of a large number of experiments to resolve the effect of elevated CO₂ concentrations on crops have confirmed a beneficial effect. The mean value yield response of C₃ crops (most crops except maize, sugar cane, millet, and sorghum) to doubled CO₂ is +30%. Measured response ranges from -10% to +80%. Only gradually is the basis for these differences being resolved. Factors known to affect the response include the availability of plant nutrients, the crop species, temperature, precipitation, and other environmental factors. Differences in experimental

technique also are responsible for variations in the measured response (High Confidence).

- Changes in soils, e.g., loss of soil organic matter, leaching of soil nutrients, and salinization and erosion, are a likely consequence of climate change for some soils in some climatic zones. Cropping practices such as crop rotation, conservation tillage, and improved nutrient management are, technically, quite effective in combating or reversing deleterious effects (High Confidence).
- Livestock production will be affected by changes in grain prices, changes in the prevalence and distribution of livestock pests, and changes in grazing and pasture productivity. Analyses indicate that intensively managed livestock systems have more potential for adaptation than crop systems. In contrast, adaptation may be more problematic in pastoral systems where production is very sensitive to climate change, technology changes introduce new risks, and the rate of technology adoption is slow (see Chapter 2) (Medium Confidence).
- The risk of losses due to weeds, insects, and diseases is likely to increase (Low Confidence).

Regional and Global Production Effects

To evaluate the direct and indirect effects of climate on yield at the farm, regional, or higher levels requires integrated models that consider system interactions. Issues of scale add uncertainty, and higher-order models have not generally taken into account the climatic effects on soils and pests. Despite these limitations, climate change studies show:

- Crop yields and productivity changes will vary considerably across regions. Thus, the pattern of agricultural production is likely to change in a number of regions (High Confidence).
- Global agricultural production can be maintained relative to base production under climate change as expressed by general circulation models (GCMs) under doubled CO₂ equilibrium climate scenarios (Medium Confidence).
- Based on global agricultural studies using doubled CO₂ equilibrium GCM scenarios, lower-latitude and lower-income countries have been shown to be more negatively affected. Again, crop model simulation results vary widely, e.g., ±20% changes in yield, for specific countries and sites across studies and GCM scenarios (Medium Confidence).

Vulnerability

Vulnerability is used here to mean the *potential* for negative consequences given the range of possible climate changes that might reasonably occur and is not a prediction that negative consequences will occur. Vulnerability can be defined at different scales, including yield, farm or farm sector, regional economic, or hunger vulnerability.

- Vulnerability to climate change depends on physical and biological response but also on socioeconomic characteristics. Low-income populations depending on isolated agricultural systems, particularly dryland systems in semi-arid and arid regions, are particularly vulnerable to hunger and severe hardship. Many of these at-risk populations are found in Sub-Saharan Africa, South and Southeast Asia, as well as some Pacific Island countries and tropical Latin America (High Confidence).

Adaptation

Uncertainty remains with regard to the ability of agricultural systems to adapt to climate change. Historically, farming systems have responded to a growing population and have adapted

to changing economic conditions, technology, and resource availabilities. It is uncertain whether the rate of change of climate and required adaptation would add significantly to the disruption likely due to future changes in economic conditions, population, technology, and resource availabilities.

- Adaptation to climate change is likely; the extent depends on the affordability of adaptive measures, access to technology, and biophysical constraints such as water resource availability, soil characteristics, genetic diversity for crop breeding, and topography. Many current agricultural and resource policies are likely to discourage effective adaptation and are a source of current land degradation and resource misuse (High Confidence).
 - National studies have shown incremental additional costs of agricultural production under climate change which could create a serious burden for some developing countries (Medium Confidence).
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13.1. Introduction

Climate change will affect agriculture through effects on crops (Section 13.2); soils (Section 13.3); insects, weeds, and diseases (Section 13.4); and livestock (Section 13.5). Climatic conditions interact with agriculture through numerous and diverse mechanisms. Mechanisms, effects, and responses include, for example, eutrophication and acidification of soils, the survival and distribution of pest populations, the effects of CO₂ concentration on tissue- and organ-specific photosynthate allocation, crop breeding aims, animal shelter requirements, and the location of production (Brunnert and Dämmgen, 1994). Variation of agricultural and climatic conditions across the world leads to different local and regional impacts (Section 13.6). High levels of uncertainty necessitate assessment of vulnerability to the adverse effects of potential climate change (Section 13.7). The effects of climate change on local, national, and regional economies and food supplies depend on future economic and agricultural conditions and on the international transmission of supply shocks through international trade (Section 13.8). Historically, agriculture has proved to be highly adaptive to changing conditions, but uncertainty remains with regard to adaptation to potential climate change (Section 13.9). Emission-control efforts also will likely affect agriculture (Chapter 23), as will competition for land and water resources from other sectors affected by climate change (Chapter 25).

13.2. Climatic Effects on Crop Plants

The main climate variables important for crop plants, as for other plants, are temperature, solar radiation, water, and atmospheric CO₂ concentration. Important differences in temperature sensitivity and response to CO₂ exist among C₃, C₄, and CAM plants (Chapter A). While the basic physiological response of crop plants are no different than other plants of similar types, crop plants have been selected for particular traits and grow under more highly controlled conditions than plants growing in forests (managed and unmanaged) or other ecosystems. Most crop plants are C₃, the principal C₄ exceptions are maize, millet, sorghum, and sugar cane. Crop traits are selected and bred into different varieties to produce high yields for different climate and resource conditions. Most crop plants are grown as annuals (e.g., grains, potatoes, and most vegetable and fiber crops) with the crop species, variety, and planting time chosen by the farmer at the start of each growing season. Tree fruits, coffee, tea, cocoa, bananas, grapes, many forage and pasture crops, and other small fruits are the principal perennials. Nutrients and water which may be limited under natural conditions are more likely to be (or can be) augmented via fertilization, irrigation, and management of crop residue. Competition with other plants is controlled. The primary focus of crop production is the efficient production of harvestable yield, usually of only one component of the plant (e.g., seed, fruit, root, leaf).

13.2.1. Elevated CO₂ and Crops

Experiments concerning crop performance at elevated CO₂ concentrations in general show a positive but variable increase in productivity for annual crops (Kimball, 1983; Strain and Cure, 1985; Cure and Acock, 1986; Allen *et al.*, 1990; Kimball *et al.*, 1990; Lawlor and Mitchell, 1991; Bazzaz and Fajer, 1992; Gifford and Morison, 1993; Koerner, 1993; Rozema *et al.*, 1993; Mooney and Koch, 1994; Rogers *et al.*, 1994). Annual C₃ plants exhibit an increased production averaging about 30% at doubled (700 ppm) CO₂ concentrations; both biomass and seed production show an increase in almost all experiments under controlled conditions (Cure and Acock, 1986; Rogers and Dahlmann, 1993). Although the mean value response (+30% for C₃ crops) has been confirmed, variations in responsiveness between plant species and ecosystems persist (from -10% to +80%), and only gradually is the basis for these differences being resolved. Fewer experiments have been conducted with perennial crops—woody species in particular—but evidence suggests that the growth response would be less than for annual crops; the measured response for C₄ crops is much smaller than that for C₃ crops.

Variations in the growth enhancement among crops and different varieties of the same crop and over years are high, and interactions with nutrient and water availability are complex (e.g., Goudriaan and De Ruiter, 1983; Chaudhuri *et al.*, 1986; Mitchell *et al.*, 1993). The extent and occurrence of physiological adaptations of the photosynthetic apparatus, particularly of perennial plants, to long-term exposure to high CO₂ concentrations—which is more directly relevant to long-term climate change—are still unresolved (Cure and Acock, 1986; Bazzaz and Fajer, 1992; Wolfe and Erickson, 1993). Plants with nitrogen-fixing symbionts (e.g., peas, beans, alfalfa), under favorable environmental conditions for both symbiont and plant, tend to benefit more from enhanced CO₂ supplies than do other plants (Cure *et al.*, 1988). The content of nonstructural carbohydrates generally increases under high CO₂, while the concentrations of mineral nutrients and proteins are reduced (Mooney and Koch, 1994; Rogers *et al.*, 1994; Koerner and Miglietta, in press). Root/shoot ratios often increase under elevated CO₂ levels favoring root crops and also contribute to soil organic matter build-up (Mauney *et al.*, 1992; Mitchell *et al.*, 1993). Crop plants, like other plants, show increased water use efficiency under elevated CO₂ levels, but water consumption on a ground-area basis vs. a leaf-area basis is much less affected. Water use on a ground-area basis can actually increase if leaf area (canopy) increases. The range of water-use efficiencies among varieties for major crops is wide (e.g., Cure and Acock, 1986; Kimball *et al.*, 1993; Sombroek and Gommers, 1993), providing the opportunity to breed or select for improved efficiency. At higher CO₂ levels, plant growth damage done by air pollutants like nitrogen oxide (NO_x), sulfur dioxide (SO₂), and ozone (O₃) is reduced because of partial stomatal closing and other physiological changes (Van de Geijn *et al.*, 1993).

The wide range in estimated responses to elevated CO₂ is due in large part to the different experimental systems employed

(Gifford and Morison, 1993), each with advantages and disadvantages (Krupa and Kickert, 1989). Year-to-year variations in response also occur because of varying weather conditions that more or less favor CO₂ response of crops. The most widely used experimental system is the open-top chamber. Free-air CO₂ enrichment (FACE) experiments are more expensive but attempt to create conditions close to those likely to be experienced in an open field. Initial results from these experiments confirm the basic positive response of crops to elevated CO₂, but studies have been conducted only for a few crops (Mauney *et al.*, 1992). In addition, even the FACE experimental set-up creates a modified area (Kimball *et al.*, 1993; Vugts, 1993) analogous to a single irrigated field within a dry environment.

13.2.2. Temperature, Moisture, and Other Variables

Plant growth and crop yields clearly depend on temperature and temperature extremes, as shown for five major food crops (Table 13-1), and vary for crops with different photosynthetic pathways (Le Houerou *et al.*, 1993). The optimum range for C₃ crops is 15 to 20°C and for C₄ crops 25 to 30°C; for CAM

crops a nighttime temperature of 10 to 20°C is optimal. C₄ and CAM crops require a minimum temperature of 10 to 15°C for growth and are relatively sensitive to frost. The minimum temperature for C₃ crops ranges from 5 to 10°C; C₃ crops exhibit variable frost sensitivity. Cumulative temperature above minimum growing temperature is an important determinant of crop phenological development. For annual crops, warmer temperatures speed development, shortening the period of growth and lowering yield if shortened growth period is not fully compensated by more rapid development at the higher temperature (Ellis *et al.*, 1990). The amount of light received during the reproductive stage may determine whether yields fall (Acock and Acock, 1993).

The variation of temperature requirements and temperature extremes for different cultivars of the same species and among species, however, is quite wide for most crops, as shown for major crops such as wheat, rice, maize, and soybean (Table 13-2). Such variation in requirements provides significant scope for adaptation through switching among existing cultivars and crops or introducing genetic variability through conventional plant breeding.

It has been suggested that higher mean temperatures will be accompanied by higher variability and more frequent occurrence of extremes (Katz and Brown, 1992). Such changes could severely affect plant functioning at low and high mean temperatures (Larcher, 1980; Kuiper, 1993).

Table 13-1: Crop physiology: Temperature thresholds (°C) of some major crops of the world (optimum range refers to the entire growing season and narrows under high light and elevated CO₂).

Crop	Optimum Range	Lower Range	Upper Range	References/Remarks
Wheat (C ₃)	17–23	0	30–35	Burke <i>et al.</i> , 1988; Behl <i>et al.</i> , 1993; optimal enzyme function and representative seasonal foliage temperature
Rice (C ₃)	25–30	7–12	35–38	Le Houerou <i>et al.</i> , 1993; Yoshida, 1981
Maize (C ₄)	25–30	8–13	32–37	Le Houerou, 1993; Decker <i>et al.</i> , 1986; Pollak and Corbett, 1993; Ellis <i>et al.</i> , 1992; Long <i>et al.</i> , 1983
Potato (C ₃)	15–20	5–10	25	Haverkort, 1990; Prange <i>et al.</i> , 1990
Soybean (C ₃)	15–20	0	35	Hofstra and Hesketh, 1969; Jeffers and Shibles, 1969

Climate variability and resultant interannual variability in yield is a fundamental feature of most cropping systems (Gommes, 1993). In temperate areas, low temperatures and/or frost occurrences are the usual limiting factor for growing season length. In tropical and subtropical areas, where temperature variation is less extreme throughout the year than in temperate areas, season-length and seasonal variation depend on regular patterns of precipitation.

Temperature, solar radiation, relative humidity, wind, and precipitation vary not only over the season and year but on a daily basis. The effects of variability can be both positive and negative depending on the crop and the nature of the variability. Cool-season vegetable crops (e.g., spinach, cauliflower, broccoli) perform best when nights are cool; their quality deteriorates under warmer temperatures. Apples, pears, cherries, and many other tree fruits require winter chilling periods for buds to set but can suffer near-total loss of the fruit crop if late frosts damage the blossoms. Alternate thawing and freezing of the ground can cause the loss of perennial forage crops such as alfalfa. Extreme climatic events (e.g., storms with high winds, flooding, heavy rains, hail, hard late or early frosts) can be responsible for severe or total crop loss.

The anticipated increase in temperatures with global warming can lead to spikelet sterility in rice, loss of pollen viability in maize, reversal of vernalization in wheat, and reduced formation of tubers and tuber bulking in potatoes for areas near critical thresholds (Table 13-3). Yield losses can be severe in these

Table 13-2: Crop phenology for important crops.

Crop	Base Temp. (°C)	Max. Devel. (°C)	Emergence to Pre-Anthesis (degree days)	Post-Anthesis to Maturity (degree days)	Reference
Wheat	0	20–25	750–1300	450–1050	Van Keulen and Seligman, 1987; Elings, 1992; Hodges and Ritchie, 1991
Rice	8	25–31	700–1300	450–850	Yoshida, 1981; Penning de Vries, 1993; Penning de Vries <i>et al.</i> , 1989
Maize	7	25–35	900–1300	700–1100	Van Heemst, 1988; Pollak and Corbett, 1993; Kiniry and Bonhomme, 1991; Rötter, 1993
Soybean	0	25–35	highly variable	450–750	Wilkerson <i>et al.</i> , 1989; Swank <i>et al.</i> , 1987

Source: Adapted from Acock and Acock, 1993.

Notes: Base Temp. = minimum temperature for growth; Max. Devel. = optimum temperature for crop development; Emergence to Pre-Anthesis = cumulative degree days needed from crop emergence to pre-anthesis (flowering); Post-Anthesis to Maturity = cumulative degree days required (after flowering) to reach maturity.

cases, if temperatures exceed critical limits for periods as short as 1 hour during anthesis (flowering). Burke *et al.* (1988) found that under ample water supply different crop species manage to maintain foliage temperature within their specific optimum range (thermal kinetic window), thereby maximizing biomass accumulation.

Species-specific optimal temperature ranges are relatively narrow compared to diurnal and seasonal foliage temperature fluctuations. If temperature variability on a daily and seasonal basis were to decrease, crop cultivars in environments with mean temperatures close to cultivar-specific optima could profit from prolonged exposure to optimum temperatures. While variability in some climatic dimensions may increase, the temperature increase since the 1940s has been due mainly to increased nighttime temperature (Kukla and Karl, 1993), thus reducing the diurnal variation of temperature and considerably influencing the nighttime respiration. The response of respiration is theoretically derived and experimentally

well-established, but the concept is challenged for situations where plants or crops are grown continuously and have adapted to the higher temperature (Gifford and Morison, 1993).

Other environmental changes will interact with changes in climate variables and elevated CO₂ to affect crop yields. Among these are exposure to O₃—tropospheric (surface) concentrations of which have doubled over the past 100 years in the Northern Hemisphere (Feister and Warmbt, 1987; Volz and Kley, 1988; Anfossi *et al.*, 1991) to a level estimated to reduce yields in the range of 1 to 30% (e.g., Ashmore, 1988; Van der Eerden *et al.*, 1988; Bosac *et al.*, 1993; Sellden and Pleijel, 1993)—and exposure to ultraviolet-B (UV-B) radiation, which is expected to increase due to stratospheric ozone depletion. UV-B fluxes depend on cloud cover (Van der Leun and Tevini, 1991) and decrease by a factor of 10 with latitude and increase with altitude. Thus, crops grown at high latitudes and high altitudes are most likely to be affected. Plant sensitivities vary widely by species (Rozema *et al.*, 1991; Tevini, 1993) and across cultivars of species, such as soybeans (Biggs *et al.*, 1981).

Table 13-3. Temperature thresholds: High temperature effects on key development stages of five major arable crops.

Crop	Effect	Reference
Wheat	Temperature >30°C for more than 8 hours can reverse vernalization	Evans <i>et al.</i> , 1975
Rice	Temperature >35°C for more than 1 hour at anthesis causes high percentage spikelet sterility	Yoshida, 1981
Maize	Pollen begins to lose viability at temperatures >36°C	Decker <i>et al.</i> , 1986
Potato	Temperatures >20°C depress tuber initiation and bulking	Prange <i>et al.</i> , 1990
Soybean	Great ability to recover from temperature stress; critical period in its development unknown	Shibles <i>et al.</i> , 1975

Source: Acock and Acock, 1993.

Some studies have investigated the combined effect of various stresses including climate, CO₂, O₃, and UV-B on crops (e.g., Goudriaan and De Ruiter, 1983; Chaudhuri *et al.*, 1986; Allen, 1990; Mitchell *et al.*, 1993; Krupa and Kickert, 1993). Results indicate that rice, barley, sorghum, soybean, oats, beans, and peas are relatively more sensitive to UV-B than other major crops and that wheat, maize, potatoes, cotton, oats, beans, and peas are relatively more sensitive to O₃. For other crops, including cassava, sugar cane, sweet potato, grapes, coconut, rye and peanuts, no clear results are available.

Consistent moisture availability throughout the crop growth period is critical. Overall, the hydrological cycle is expected to intensify with higher evaporation, air humidity, and precipitation. Higher temperatures would, at the same time, increase crop water demand. Global studies have found a tendency for increased evaporative demand to exceed precipitation increase

Box 13-1. Modeling Crop Response to Environmental Change

Climatic and other factors strongly interact to affect crop yields. Models have provided an important means for integrating many different factors that affect crop yield over the season (Rötter, 1993). Scaling up results from detailed understanding of leaf and plant response to climate and other environmental stresses to estimate yield changes for whole farms and regions, however, can present many difficulties (e.g., Woodward, 1993).

Higher-level, integrated models typically accommodate only first-order effects and reflect more complicated processes with technical coefficients. Mechanistic crop growth models take into account (mostly) local limitations in resource availability (e.g., water, nutrients) but not other considerations that depend on social and economic response, such as soil preparation and field operations, management of pests, and irrigation.

Models require interpretation and calibration when applied to estimating commercial crop production under current or changed climate conditions (see Easterling *et al.*, 1992; Rosenzweig and Iglesias, 1994); in cases of severe stress, reliability and accuracy in predicting low yields or crop failure may be poor. With regard to the CO₂ response, recent comparisons of wheat models have shown that even though basic responses were correctly represented, the quantitative outcome between models varied greatly. Validation of models has been an important goal (Olesen and Grevsen, 1993; Semenov *et al.*, 1993a, 1993b; Wolf, 1993a, 1993b; Delecolle, 1994; Iglesias and Minguez, 1994; Minguez and Iglesias, 1994).

Further integration of models of crop yield, phenology, and water use with geographic-scale agroclimatic models of crop distribution and economic response has also occurred (e.g., Kaiser *et al.*, 1993; Kenny *et al.*, 1993; Rötter and van Diepen, 1994). Simplified representations of crop response have been used with climate and soil data that are available on a global basis (Leemans and Solomon, 1993). More aggregated statistical models have been used to estimate the combined physical and socioeconomic response of the farm sector (Mendelsohn *et al.*, 1994; Darwin *et al.*, 1995).

Incorporation of the multiple effects of CO₂ in models has generally been incomplete. Some do not include any CO₂ effects and thus may overestimate negative consequences of CO₂-induced changes in climate. Other models consider only a crude yield effect. More detailed models consider CO₂ effects on water use efficiency (e.g., Wang *et al.*, 1992; Leuning *et al.*, 1993). With few exceptions, most models fail to consider CO₂ interactions with temperature and effects on reproductive growth (Wang and Gifford, 1995).

in tropical areas (Rosenzweig and Parry, 1994), but this result varies locally and across climate scenarios. Large changes in the seasonal pattern of rainfall or changes in the consistency of rainfall within the crop growing season would likely matter more for annual crops than changes in annual precipitation and potential evaporation rates. Some studies suggest increased intensity of rainfall, which may result in increased runoff (Whetton *et al.*, 1993). Changes in large-scale atmospheric patterns such as the El Niño/Southern Oscillation (ENSO) and tropical monsoons could cause significant shifts in rainfall patterns, with consequent effects on agricultural production. ENSO events currently have widespread and well-documented impacts on production in Oceania, Latin America, Africa, South and Southeast Asia, and the United States (Folland *et al.*, 1990, 1991; McKeon *et al.*, 1990; Nicholls and Wong, 1990; McKeon and White, 1992; Rimmington and Nicholls, 1993), but climate scientists have not resolved how ENSO events may be affected by long-term climate change.

A variety of models (see Box 13-1) that integrate understanding of crop yield and climate relationships have been used for estimating changes in potential crop yield, zonal production shifts, and regional and global production (see Sections 13.5 and 13.8.2).

13.3. Soil Changes and Agricultural Practices

Climate affects most major soil processes and is a major factor in soil formation; the potential effects of changing climate and higher atmospheric CO₂ on soils are highly interactive and complex (Bouwman, 1990; Buol *et al.*, 1990). Many of the world's soils are potentially vulnerable to soil degradation (e.g., loss of soil organic matter, leaching of soil nutrients, salinization, and erosion) as a likely consequence of climate change (see Chapter 4).

Cropping practices that maintain a more closed ground cover over longer periods—including crop rotation, planting of cover crops, and reduced or minimum tillage—combined with integrated nutrient management are quite effective in combating or reversing current land degradation and would be similarly effective where climate change had the potential to exacerbate land degradation (Brinkman and Sombroek, 1993; Rasmussen and Collins, 1991; Logan, 1991). Brinkman and Sombroek (1993) found that, in most cases, changes in soils by direct human action, whether intentional or unintended, are likely to have a greater impact than climate change. They found that under a transient scenario of climate change, soil physical, chemical, and biological processes will be given time to adapt, thereby counteracting human-induced land degradation.

13.4. Weeds, Insects, and Diseases

Weeds, insects, and pathogen-mediated plant diseases are affected by climate and atmospheric constituents. Resultant changes in the geographic distribution of these crop pests and their vigor in current ranges will likely affect crops. Existing research has investigated climatic determinants of the range of many pests, but the potential changes in crop losses due to climatically driven changes in pests have not been included in most agricultural impact studies (Waggoner, 1983; Stinner *et al.*, 1987; Prestidge and Pottinger, 1990).

13.4.1. Weeds

Weeds will benefit from the “CO₂ fertilization effect” and from improvements in water use efficiency associated with increasing CO₂ concentrations, but the impact on crop production will depend on how enhanced-growth weeds compete with enhanced-growth crops. Of the 86 plant species that contribute 90% of per capita food supplies worldwide, 80 are C₃ plants (Prescott-Allen and Prescott-Allen, 1990), while 14 of the world’s 18 worst weeds are C₄ plants (Holm *et al.*, 1977). Experiments generally show C₃ species to benefit from CO₂ enrichment at the expense of C₄ species (Patterson and Flint, 1980, 1990; Carter and Peterson, 1983; Patterson *et al.*, 1984; Wray and Strain, 1987; Bazzaz and Garbutt, 1988).

Regarding temperature, most weeds of warm season crops originate in tropical or warm temperate areas and are responsive to small increases in temperature. For example, the growth of three leguminous weeds increased significantly as day/night temperature increased (Flint *et al.*, 1984). Biomass of C₄ smooth pigweed (*Amaranthus hybridus*) increased by 240% for an approximate 3°C temperature increase; C₄ grasses also showed large increases (Flint and Patterson, 1983; Patterson, 1993).

Accelerated range expansion of weeds into higher latitudes is likely (Rahman and Wardle, 1990; Patterson, 1993) as demonstrated for itchgrass (*Rottboellia cochinchinensis*, Lour.), cogongrass (*Imperata cylindrica*), Texas panicum (*Panicum texanum*), and witchweed (*Striga asiatica*) (Patterson *et al.*, 1979; Patterson, 1995). However, not all exotic weeds will be favored by climatic warming. Patterson *et al.* (1986) found loss of competitiveness under warmer conditions for the southward spread of wild proso millet (*Panicum miliaceum*) in the southwestern United States.

Increasing CO₂ and climate change probably will also affect mechanical, chemical, and natural/biological efforts to control weeds (Patterson, 1993, 1995), which currently cause worldwide crop production losses of about 12% (25% for traditional production systems) (Parker and Fryer, 1975). Environmental factors including temperature, precipitation, wind, soil moisture, and atmospheric humidity influence when herbicides are applied, as well as their uptake and metabolism by crops and target weeds (Hatzios and Penner, 1982; Muzik, 1976). High leaf starch concentrations, which commonly

occur in C₃ plants grown under CO₂ enrichment (Wong, 1990), might interfere with herbicide activity. CO₂ enrichment also increases the growth of rhizomes and tubers in C₃ plants (Oechel and Strain, 1985), which could reduce the effectiveness of chemical and mechanical control of deep-rooting, perennial C₃ weeds. On the other hand, increased temperatures and increased metabolic activity tend to increase uptake, translocation, and effectiveness of many herbicides. Natural and biological control of weeds and other pests depends on the synchrony between the growth, development, and reproduction of biocontrol agents and their targets. Such synchrony may be disrupted if climate changes rapidly, particularly if climatic extremes occur more frequently. Global warming could facilitate overwintering of insect populations and favor earlier poleward migrations in the spring, which could increase the effectiveness of biological control of weeds in some cases. Conversely, such enhanced over-winterings would accelerate the spread of viruses by migrating vectors like aphids.

13.4.2. Insect Activity and Distribution

Climate change will affect the distribution and degree of infestation of insect pests through both direct effects on the life cycle of insects and indirectly through climatic effects on hosts, predators, competitors, and insect pathogens. There is some evidence that the risk of crop loss will increase due to poleward expansion of insect ranges. Insect populations faced with modified and unstable habitats created under annual arable agricultural systems generally must diapause (enter a state of dormancy), migrate, otherwise adapt genetically, or die. Insect species characterized by high reproduction rates are generally favored (Southwood and Comins, 1976). Human alteration of conditions that affect host plant survival—irrigation, for example—also affects phytophagous (leaf-eating) insect populations.

Insect life cycle processes affected by climate and weather include lifespan duration, fecundity, diapause, dispersal, mortality, and genetic adaptation. Porter *et al.* (1991) list the following effects of temperature on insects: limiting geographical ranges; over-wintering; population growth rates; number of generations per annum; length of growing season; crop-pest synchronization; interspecific interactions; dispersal and migration; and availability of host plants and refugia. The effects of climate and weather on insect life cycles have been documented for a wide variety of insect pests of agriculture, rangelands, and forests (Dobzhansky, 1965; Fye and McAda, 1972; Tauber *et al.*, 1986; Mattson and Haack, 1987; Kingsolver, 1989; Cammell and Knight, 1991; Harrington and Stork, 1995). Many effects involve changes in the severity of outbreaks following extreme weather events (on the order of hours to weeks). Freezing temperatures are a major factor in mortality, but *Drosophila* sp. insects that survive relatively colder temperatures have been found to be more fecund than cohorts that were not exposed to the low temperatures (Dobzhansky, 1965). Temperatures that exceed critical thresholds frequently have adverse effects on fecundity, as in the cases

of bollworm, *Helicoverpa zea* (Boddie); tobacco budworm, *Heliothis virescens* (F.); beet armyworm, *Spodoptera exigua* (Hübner); cabbage looper, *Trichoplusia ni* (Hübner); saltmarsh caterpillar, *Estigmene acrea* (Drury); and pink bollworm, *Pectinophora gossypiella* (Saunders) (Fye and McAda, 1972).

Abnormally cool, wet conditions are associated with high subsequent infestations of cotton by cotton tipworm, *Crociosema plebejana* (Zeller) (Hamilton and Gage, 1986). November precipitation and April temperature are the best indicators of mean grasshopper densities in Southern Idaho (Fielding and Brusven, 1990). Drought can affect various physiological processes of plants, which may increase the plants' attractiveness and susceptibility to phytophagous insects (Mattson and Haack, 1987). Intense precipitation has been noted as a deterrent to the occurrence and success of oviposition by insects such as the European corn borer, *Ostrinia nubilalis* (Hübner) (Davidson and Lyon, 1987). Abundant precipitation can affect mortality, for example, through drowning of soil-dwelling insects (Watt and Leather, 1986) but is more likely to affect insects indirectly through climatic effects on insect pathogens, predators, and parasites, as has been shown for *H. zea* pupae especially under persistently saturated soil conditions (Raulston *et al.*, 1992).

While the specific ways in which climate change could affect persistent wind patterns such as nocturnal wind jets in the United States and convergence systems such as the Inter-Tropical Convergence Zone (ITCZ) are poorly predicted by GCMs, changes in the strength, timing, and geographical extent of these systems have been hypothesized. Important insect pests of agriculture currently use these systems to disperse widely from decaying habitats to viable habitats (Pedgley, 1982). Corn earworm, *H. zea* moths in the United States (Westbrook *et al.*, 1985; Scott and Achtemeier, 1987; Lingren *et al.*, 1993), grasshoppers or locusts [*Ailopus simulatrix* (Walker)], old world bollworm [*Heliothis armigera* (Hübner)], and whitefly [*Bemisia tabaci* (Gennadius)] disperse via atmospheric transport. In the case of the ITCZ and locusts, the winds also contribute ephemeral precipitation for host plants as reviewed by Joyce (1983) and Rainey (1989). Changes in these systems would affect the speed and range of dispersal of these pests.

Many of the documented effects of climate on insects are based on unusual weather events affecting the severity of insect outbreaks within their normal range or the (unintended) introduction of exotic species into new environments or extension of (host) crops into new environments (e.g., through irrigation). Human-induced local climate change within urban areas provides evidence of how insects can adapt to changes in their environment. Examples of genetic adaptation include: froggatt (*Dacus tryoni*), lucerne flea (*Sminthurus viridis* L.) and sheep blowfly (*Lucilia cuprina*) (Wied.) in Australia after introduction from Europe or with the expansion of crop areas; the European corn borer, *O. nubilalis* (Hübner) and the European spruce sawfly, *Gilpinia hercyniae* (Hartig) in North America after introduction from Europe; and *Drosophila serrata*

Mallock across latitudes (Birch, 1965). *Drosophila serrata* Mallock also has responded by natural selection to the changed conditions in large cities (Dobzhansky, 1965). Selection to tighten host-insect interaction [such as codling moth, *Cydia pomonella* (L.), in fruit trees] appears to favor the evolution of isolated host races (Poshly and Bush, 1979). Climatic, agronomic, political, and economic factors jointly led to populations of boll weevil, *Anthonomus grandis grandis* Boheman, which adapted differently across cotton areas in the United States (Terranova *et al.*, 1990). Although insect populations have been redistributed during periods of major climatic change, a continuous intermixing of beetle species' gene pools in the Rocky Mountains of the United States was determined to have prevented speciation (Elias, 1991).

Understanding of insect physiological development and behavior has led to the development of numerical models that estimate insect growth, movement, and mortality in response to potential changes in climate (Goodenough and McKinion, 1992). Minimum and maximum temperatures, required cumulative degree days, and, where important, the effects of drought or wet conditions (which are the basis for such models), have been established for many common agricultural pests (e.g., Fye and McAda, 1972; Davidson and Lyon, 1987). Simulation models predict potential redistribution of insects under simulated climates.

Specific studies of the likely impacts of climate change were reviewed by Cammel and Knight (1991), Porter *et al.* (1991), Sutherst (1990, 1991), and Sutherst *et al.* (1995). They demonstrate that impacts could be severe in many different environments and involve numerous different species of insect pests. Principal concern is with species that can increase their population size by undergoing an extra generation each year in warmer climates or expand their geographical distributions. For example, Porter *et al.* (1991) found that in Europe *O. nubilalis* would shift 1220 km northward if temperature increased by 3° to 6°C by 2025–2070. For a 3°C temperature increase in Japan, Mochida (1991) predicted expanded ranges for tobacco cut worm (*Spodoptera litura*), southern green stink bug (*Nezera viridula*), rice stink bug (*Lagynotomus eleongatus*), lima-bean pod borer (*Etiella zinckenella*), common green stink bug (*Nezera antennata*), soybean stem gall (*Asphondylia* sp.), rice weevil (*Sitophilus oryzae*), and soybean pod borer (*Legumunuvora glycinivorella*), but a decreased range for rice leaf beetle (*Oulema oryzae*) and rice leaf miner (*Agromyza oryzae*). Vegetation subzones were linked with microclimates to extrapolate spruce weevil hazard zones in British Columbia (Spittlehouse and Sieben, 1994). Models that match the presence of particular species with discrete ranges of temperature and precipitation parameters such as CLIMEX may be especially appropriate for projecting the effects of climate change on insect redistribution (Worner, 1988; Sutherst *et al.*, 1995).

Actual insect distributions under climate change will also depend on host distributions (Rainey, 1989), competition with existing species (DeBach, 1965), adaptability to new conditions, and the presence of natural enemies in the area. Because

climate effects on insect life cycles frequently depend on extreme events (e.g., freezing, intense precipitation) and climatic features such as the persistent winds of the Inter-Tropical Convergence system, the reliability of predicted redistribution of insects depends, in part, on the reliability of predictions of these features of climate.

13.4.3. Plant Diseases

The occurrence of plant fungal and bacterial pests depends on temperature, rainfall, humidity, radiation, and dew. Climatic conditions affect the survival, growth, and spread of pathogens, as well as the resistance of hosts. Friedrich (1994) summarizes the observed relationship between climatic conditions and important plant diseases. Among these, mild winters have been associated with more rapid and stronger outbreaks of powdery mildew (*Erysiphe graminis*), brown leaf rust of barley (*Puccinia hordei*), and strip rust of cereals (*Puccinia striiformis*) (Meier, 1985). Mild winters combined with very warm weather conditions provide optimal growth conditions for cercospora leaf spot disease (*Cercospora beticola*), powdery mildew (*Erysiphe betae*), and rhizomania disease (*Rhizomania*) (Treharne, 1989). Warm, humid conditions lead to earlier and stronger outbreaks of late potato blight (*Phytophthora infestans*) (Löpmeyer, 1990; Parry *et al.*, 1990). Dry and hot summers generally reduce infestations of most fungal diseases because plant resistance is increased. Summer dryness, particularly in early summer, also decreases rhynchosporium leaf blotch (*Rhynchosporium secalis*) and septoria leaf spot diseases (*Septoria tritici* and *S. nodorum*), but more frequent summer precipitation, particularly heavy storms, would increase incidences of these diseases because rain and rain-borne splash water is the means by which disease spores are spread (Royle *et al.*, 1986). Warmer temperatures would likely also shift the occurrence of these diseases into presently cooler regions (Treharne, 1989).

13.5. Animal Agriculture

Climate affects animal agriculture in four ways: through (1) the impact of changes in livestock feedgrain availability and price (e.g., Adams *et al.*, 1990; Bowes and Crosson, 1993; Kane *et al.*, 1993; Rosenzweig and Parry, 1994); (2) impacts on livestock pastures and forage crops (Wilson, 1982; Martin *et al.*, 1991; Easterling *et al.*, 1993; McKeon *et al.*, 1993); (3) the direct effects of weather and extreme events on animal health, growth, and reproduction (Bianca, 1970; Rath *et al.*, 1994); and (4) changes in the distribution of livestock diseases (Stem, 1988; U.S. EPA, 1989).

Generally, the impacts of changes in feedgrain prices or forage production on livestock production and costs are moderated by markets. Impacts of changes in feedgrain supply on the supply of meat, milk, egg, and other livestock products in terms of price increase is substantially less than the initial feedgrain price shock (Reilly *et al.*, 1994). Bowes and Crosson (1993)

demonstrated the importance of feed exports or imports into a region in determining downstream impacts on livestock and meatpacking industries. Abel and Levin (1981) found that, for developing country agriculture, livestock are a better hedge against losses than are crops because animals are better able to survive extreme weather events such as drought. The relatively lower sensitivity of livestock to climate change is also documented for the historical case of the U.S. Dust Bowl experience of the 1930s (Waggoner, 1993).

The impact of climate on pastures and unimproved rangelands may include deterioration of pasture quality toward poorer quality, subtropical (C_4) grasses in temperate pastoral zones as a result of warmer temperatures and less frost, or increased invasion of undesirable shrubs—but also potential increases in yield and possible expansion of area if climate change is favorable and/or as a direct result of increasing CO_2 (Martin *et al.*, 1993; McKeon *et al.*, 1993; Salinger and Porteus, 1993; Campbell *et al.*, 1995). (See Chapter 2 for details on possible changes in species composition of rangelands and effects on pastoral agriculture.)

Heat stress has a variety of detrimental effects on livestock (Furquay, 1989), with significant effects on milk production and reproduction in dairy cows (Johnston, 1958; Thatcher, 1974; Khan, 1991; Orr *et al.*, 1993). Swine fertility shows seasonal variation due to seasonal climate variability (Claus and Weiler, 1987). Reproductive capabilities of dairy bulls and boars and conception in cows are affected by heat stress (Egbunike and Elmo, 1978; Cavestany *et al.*, 1985; Berman, 1991). Livestock management and development of breeds better-suited to tropical climates has been a specific consideration (Bonsma, 1949; Du Preez *et al.*, 1990).

Analyses suggest that warming in the tropics and in the subtropics during warm months would likely impact livestock reproduction and production negatively (e.g., reduced animal weight gain, dairy production, and feed conversion efficiency) (Hahn *et al.*, 1990; Baker *et al.*, 1993; Klinedinst *et al.*, 1993; Rath *et al.*, 1994). Results are mixed for impacts in temperate and cooler regions: forage-fed livestock generally do better (due to more forage) but more capital-intensive operations, like dairy, are negatively affected (Parry *et al.*, 1988; Baker *et al.*, 1993; Klinedinst *et al.*, 1993). Warming during the cold periods for temperate areas would likely be beneficial to livestock production due to reduced feed requirements, increased survival of young, and lower energy costs.

Impacts may be minor for relatively intense livestock production systems (e.g., confined beef, dairy, poultry, swine) because such systems control exposure to climate and provide opportunity for further controls (e.g., shading, wetting, increasing air circulation, air conditioning, and alterations of barns and livestock shelters). Livestock production systems that do not depend primarily on grazing are less dependent on local feed sources, and changes in feed quality can be corrected through feed supplements. The fact that livestock production is distributed across diverse climatic conditions from

cool temperate to tropical regions provides evidence that these systems are adaptable to different climates.

Many studies of climate and weather impacts on livestock find that the principal impacts are an increased role for management, adoption of new breeds in some cases where climate changes are moderate (for example, Brahman cattle and Brahman crosses are more heat- and insect-resistant than breeds now dominant in Texas and Southern Europe), and introduction of different species in some cases of extreme weather changes (Entwistle, 1974; Hahn, 1988, 1994; Hahn *et al.*, 1990; Baker *et al.*, 1993; Baker, 1994; Klinedinst *et al.*, 1993; Rath *et al.*, 1994).

13.6. Regional Climate Impacts: Studies and Issues

Variation of agriculture systems, climates, resources, and economic characteristics across and within countries may be more important in determining the effects of climate change than differences in climate scenarios themselves. Agricultural policy is an important consideration in most regions. Agricultural policies have had many and changing goals. Climate change is generally not among top policy priorities for agricultural policymakers, but climate change could affect the cost and likelihood of achieving other policy priorities—such as food adequacy and reduction of chronic hunger, improving export competitiveness, assuring regional and national economic and social development, increasing farm income and the viability of rural communities, assuring water availability and quality, reducing or reversing land degradation

and soil loss through erosion, and other conservation and environmental objectives.

13.6.1. Africa and the Middle East

While Africa, particularly sub-Saharan Africa, is highly dependent on agriculture, relatively little quantitative work has been done on the impacts of climate change. Little or no effort has been devoted to studying agricultural effects on countries of the Middle East. The available studies for sub-Saharan Africa suggest that critical thresholds are related to precipitation and the length of the growing season, although warmer temperatures and increased radiation may benefit highland areas. National and local assessments providing a detailed understanding of crop-specific responses and regional impacts are still lacking.

Recent studies (Ominde and Juma, 1991; Ottichilo *et al.*, 1991; Downing, 1992; Schulze *et al.*, 1993; Sivakumar, 1993; Magadza, 1994) indicate that most of Africa will be sensitive to climate change, although some regions may benefit from warmer and wetter conditions (Table 13-4). Downing (1992), in analyses for Kenya, Zimbabwe, and Senegal, evaluated the sensitivity to incremental climatic variations suggested by GCM scenarios for the region. Nationally, he estimated that potential food production in Kenya would increase, particularly if rainfall increases, but that the impacts would vary regionally; sub-humid and semi-arid provinces supporting socioeconomically vulnerable groups would be negatively affected even with increases in national food production potential.

Table 13-4: Selected crop studies for Africa and the Middle East.

Study	Scenario	Geographic Scope	Crop(s)	Yield Impact (%)	Other Comments
Eid, 1994	GISS, GFDL, UKMO	Egypt	Wheat Maize	-75 to -18 -65 to +6	w/ CO ₂ effect; also temperature and precip. sensitivity; adaptation would require heat-resistant variety development
Schulze <i>et al.</i> , 1993	+2°C (1)	South Africa	Biomass Maize	decrease increase	Mapped results, not summarized as average change for entire region
Muchena, 1994	GISS, GFDL, UKMO	Zimbabwe	Maize	-40 to -10	w/ CO ₂ effect; also temperature and precip. sensitivity; adaptations (fertilizer and irrigation) unable to fully offset yield loss
Downing, 1992	+2/+4°C, ±20% precip.	Zimbabwe Senegal Kenya	Maize Millet Maize	-17 to -5 -70 to -63 decrease	Food availability estimated to decline in Zimbabwe; carrying capacity fell 11 to 38% in Senegal; overall increase for all crops in Kenya with zonal shifts
Akong'a <i>et al.</i> , 1988	Historical droughts, sensitivity	Kenya	Maize, livestock	negative effects of drought	Considered broader socioeconomic impacts, small-holder impacts, and policy implications
Sivakumar, 1993	1945–64 vs. 1965–88	Niger, West Africa	Growing season	reduced 5–20 days	Crop variety development, timely climate information seen as important adaptation strategies

Akong'a *et al.* (1994) and Sivakumar (1993) considered the effects of climatic variability (primarily periodic droughts) on agriculture in some areas of the region, finding that such droughts have significant negative effects on production, crop season length, and higher-order social impacts. The persistence of such periodic droughts and the potential for them to change in frequency and severity in the Sahel and in eastern and southern Africa indicate the need for further research to develop adaptive strategies. The effects of greater frequency and severity include growing aridity in the savannas; deforestation and soil erosion in all farming systems but particularly in the humid, sub-humid, and equatorial regions; and salinization of irrigated lands. The economies of countries of North Africa and the Middle East are generally less dependent on agriculture than are those of sub-Saharan Africa. One study

for Egypt (Eid, 1994) indicated the potential for severe impacts on national wheat and maize production.

13.6.2. South and Southeast Asia

South and Southeast Asia include the southern portion of Asia, from Pakistan in the west to Vietnam in the east, as well as Indonesia and the Philippines. Seasonal monsoons are a dominant climate feature that affect agriculture. Matthews *et al.* (1994a, 1994b) have estimated the impacts on rice yields for many countries in the region for equilibrium climate scenarios of three major GCMs that predict temperature and precipitation increases for the region. The results show substantial variation in impact across the region and among the GCMs (Table 13-5).

Table 13-5: Selected crop studies for South and Southeast Asia.

Study	Scenario	Geographic Scope	Crop(s)	Yield Impact (%)	Other Comments
Rosenzweig and Iglesias (eds.), 1994 ¹	GCMs	Pakistan	Wheat	-61 to +67	UKMO, GFDL, GISS, and +2°C, +4°C, and ±20% precip; range is over sites and GCM scenarios with direct CO ₂ effect; scenarios w/o CO ₂ and w/ adaptation also were considered; CO ₂ effect important in offsetting losses of climate-only effects; adaptation unable to mitigate all losses
		India	Wheat	-50 to +30	
		Bangladesh	Rice	-6 to +8	
		Thailand	Rice	-17 to +6	
		Philippines	Rice	-21 to +12	
Qureshi and Hobbie, 1994	average of 5 GCMs	Bangladesh	Rice	+10	GCMs included UKMO, GFDLQ, CSIRO9, CCC, and BMRC; GCM results scaled to represent 2010; includes CO ₂ effect
		India	Wheat	decrease	
		Indonesia	Rice	-3	
			Soybean	-20	
			Maize	-40	
			Wheat	-60 to -10	
		Philippines	Rice	decrease	
		Sri Lanka	Rice	-6	
			Soybean	-3 to +1	
			Coarse Grain	decrease	
Parry <i>et al.</i> , 1992	GISS	Indonesia	Coconut	decrease	Low estimates consider adaptation; also estimated overall loss of farmer income ranging from \$10 to \$130 annually
			Rice	approx. -4	
			Soybean	-10 to increase	
			Maize	-65 to -25	
		Malaysia	Rice	-22 to -12	Maize yield affected by reduced radiation (increased clouds); variation in yield increases; range is across seasons
			Maize	-20 to -10	
			Oil Palm	increase	
			Rubber	-15	
		Thailand sites	Rice	-5 to +8	Range across GISS, GFDL, and UKMO GCM scenarios and crop models; included direct CO ₂ effect; varietal adaptation was shown to be capable of ameliorating the detrimental effects of a temperature increase in currently high-temperature environments
		India	Rice	-3 to +28	
Matthews <i>et al.</i> , 1994a, 1994b	3 GCMs	Bangladesh		-9 to +14	
		Indonesia		+6 to +23	
		Malaysia		+2 to +27	
		Myanmar		-14 to +22	
		Philippines		-14 to +14	
		Thailand		-12 to +9	

¹ Country studies were by Qureshi and Iglesias, 1994; Rao and Sinha, 1994; Karim *et al.*, 1994; Tongyai, 1994; and Escaño and Buendia, 1994, for Pakistan, India, Bangladesh, Thailand, and the Philippines, respectively.

Spikelet sterility emerged as a major factor determining the differential predictions; where current conditions were near critical thresholds, a difference in mean temperature of less than a degree resulted in a positive yield change rapidly becoming a large decline. However, genetic variability among varieties suggests relative ease in adapting varieties to new climate conditions. Temperature effects alone were generally found to reduce yields, but CO₂ fertilization was a significant positive effect.

Brammer *et al.* (1994) conclude that, among other things, the diversity of cropping systems does not allow a conclusion of magnitude or direction of impact to be made for Bangladesh at this time. Parry *et al.* (1992) showed yield impacts that vary across the countries of Thailand, Indonesia, and Malaysia and across growing season. Coastal inundation was also estimated to be a threat to coastal rice and to fish, prawn, and shrimp ponds. These authors estimated that a 1-meter sea-level rise could cause a landward retreat of 2.5 km in Malaysia; such a rise was estimated to threaten 4200 ha of productive agricultural land, an area equal to slightly less than 1% of Malaysia's paddy rice area. Model results showed that under Goddard

Institute for Space Studies (GISS) doubled CO₂ climates, erosion rates in three Malaysian river basins increased from 14–40%, and soil fertility declined on average by 2–8%.

13.6.3. East Asia

Several major studies have been conducted for countries in East Asia, including China (mainland and Taiwan), North and South Korea, and Japan. Possible climatic impacts span a wide range depending on the climate scenario, geographic scope, and study (Table 13-6). For China, results show generally negative yield effects but range from less than 10% (Zhang, 1993) to more than 30% (Jin *et al.*, 1994). While finding large changes for all of China, Hulme *et al.* (1992) conclude that to a certain extent, warming would be beneficial, with increasing yield due to diversification of cropping systems. However, they estimated that by 2050, when they expect an average warming for China of 1.2°C, increased evapotranspiration would generally exceed increases in precipitation, thus leading to a greater likelihood of yield loss due to water stress for some rice-growing areas, even as the area suitable for rice increases.

Table 13-6: Selected crop studies for East Asia.

Study	Scenario	Geographic Scope	Crops	Yield Impact (%)	Other Comments
Tao, 1992	2 x CO ₂ +1°C	China	Wheat Rice Cotton, Fruits, Oil Crops, Potatoes, Corn	-8 -6 -4 to +1	Agricultural productivity loss >5%; included direct CO ₂ effect; positive effects in NE and NW; negative in most of the country; no change in SW
Zhang, 1993	+1.5°C	South of China	Rice	-11 to -7	Double-crop; included direct CO ₂ effect
Jin <i>et al.</i> , 1994	GCMs	South of China	Rainfed Rice Irrigated Rice	-78 to -6 -37 to +15	Range across GISS, GFDL, and UKMO scenarios; no consideration of enrichment effects of CO ₂
Sugihara, 1991	2 x CO ₂ +3°C	Japan	Rice	+10	
Suyama, 1988	+2°C	Japan	Temperate Grass	-10 to +10	Average +5.6% in productivity for grass; included direct CO ₂ effect
Yoshino, 1991	+2°C	Japan	Sugar Cane	-8	Rainfall was reduced 25 to 30%, May to October
Seino, 1994	GISS, GFDL, UKMO	Japan	Rice Maize Wheat	-11 to +12 -31 to +51 -41 to +8	Impacts vary by GCM scenarios and area; included direct CO ₂ effect; generally positive in N and negative in S
Horie, 1993	GCMs	Hiroshima and Akita, Japan	Rice	-45 to +30	Estimated 14% increase for all of Japan; range based on different crop models, GCMS, and across sites; included direct CO ₂ effect; Akita more favorable than Hiroshima
Matthews <i>et al.</i> , 1994a, 1994b	GCMs	South Korea Mainland China Taiwan Japan	Rice	-22 to +14 -18 to -4 +2 to +28 -28 to +10	Range across GISS, GFDL, and UKMO scenarios and crop models; included direct CO ₂ effect; varietal adaptation capable of ameliorating the effects of a temperature increase in currently hot environments

For China, warming would likely cause a general northward movement of agroclimatic regions, with certain exceptions in the south where the moisture deficit may increase even more than in the north. The general possibility of increased summer dryness in the continental mid-latitudes suggests the following six areas as most likely to be negatively affected by climate change (Lin Erda, 1994): the area around the Great Wall lying southeast of the transition belt between crop agriculture and animal husbandry; the Huang-Hai Plains where dryland crops like wheat, cotton, corn, and fruit trees are grown; the area north of Huai River including Eastern Shandong that lies along the south edge of the south temperate zone; the central and southern areas of Yunnan Plateau; middle and lower reaches of Yangtze River; and the Loess Plateau. In general, these areas would be at heightened risk of drought and would suffer potential increases in soil erosion. The Yunnan Plateau, with generally abundant rainfall, is subject to alternating droughts and waterlogging; production is sensitive to changes that would increase the variability of climate.

Indices of vulnerability based on physical productivity and socioeconomic capability to adapt show that among China's thirty provinces, Shanxi, Inner Mongolia, Gansu, Hebei, Qinghai, and Ningxia are particularly vulnerable and less able to adapt to climate change. These seven provinces produced 12% of China's total agricultural output value in 1990 (*Statistical Yearbook of Agriculture of China*, 1991). Thus, the areas along the Great Wall and Huang-Hai Plains are areas that are both socioeconomically and agronomically vulnerable to climate change and also are areas where climate projections suggest possible adverse changes in climate.

Climate change will occur against a steadily increasing demand for food in China over the next 55 years (Lu and Liu, 1991a, 1991b). The increased annual cost of government investment only (excluding farmers' additional costs) in agriculture due to climate change through 2050 was estimated at 3.48 billion U.S. dollars (17% of the cost of government investment in agriculture in 1990).

Studies for Japan (Table 13-6) indicate that the positive effects of CO₂ on rice yields would generally more than offset negative climatic effects in the central and northern areas, leading to yield gains; in the southwest, particularly in Kyushu, the rice yield effects were, on balance, estimated to be negative for several climate scenarios (Seino, 1993a, 1993b). Horie (1987) found generally negative effects on rice yield in Hokkaido under the GISS climate scenario when rice variety was not changed but found increased yields if longer maturing varieties were adopted. Horie (1991), under the Oregon State University (OSU) climate scenario, found that rice yields would fall in most areas of the country but that changes in rice variety and other management changes could recover most losses except in the southwest, where the projected increase in temperature of 4.0–4.5°C exceeded the temperature tolerances of japonica rice varieties. Additional considerations for Japanese agriculture are possible changes in flowering and maturation of fruit trees, with potential northward shifts in cultivated areas and changed distribution of insect pests (Seino, 1993a).

13.6.4. Oceania and Pacific Island Countries

Oceania includes Australia, New Zealand, Papua New Guinea, and numerous small islands and coral atolls of the Pacific Island Countries (PICs).

Findings for Australia include: (1) poleward shifts in production, (2) varying impacts on wheat including changes in grain quality, (3) likely inadequate chilling for stone fruit and pome fruit and lower fruit quality, (4) increased likelihood of heat stress in livestock, particularly dairy and sheep, (5) increased infestation of tropical and subtropical livestock parasites but possible decreases for other species, (6) livestock benefits due to warmer and shorter winters, (7) increased damage due to floods and soil erosion, (8) increased drought potential with wheat and barley more sensitive than oats, (9) changes in the severity of outbreaks of downy mildew on grapevines and rust in wheat, and (10) beneficial effects of elevated CO₂ levels for many agricultural crops (Hobbs *et al.*, 1988; Nulsen, 1989; Pittock, 1989; Wardlaw *et al.*, 1989; Blumenthal *et al.*, 1991; Wang *et al.*, 1992; CSIRO, 1993; Hennessy and Clayton-Greene, 1995; Wang and Gifford, 1995).

Studies of New Zealand agriculture considered the main effects of climate change on New Zealand's important pastoral agriculture to be: (1) a poleward spread of subtropical pastures, (2) a resultant decrease in the area of temperate pasture, (3) higher yields, (4) altered seasonality of production, (5) spread of growth to higher elevations, and (6) decreased growth in the eastern areas of the North Island due to drier and warmer conditions (Ministry for the Environment, 1990; Salinger and Hicks, 1990; Martin *et al.*, 1991). Models to predict effects on forage production systems are currently being developed and validated. Initial modeling simulations of the effects of doubled-CO₂ climates on pasture yield including the beneficial effects of CO₂ varied from +10 to +77% (Korte *et al.*, 1991; Butler *et al.*, 1991; Martin *et al.*, 1991). The higher figures, however, likely overestimated the beneficial effects of CO₂ (Campbell, 1994). More recent work (Campbell *et al.*, 1995; Newton *et al.*, in press) indicates gains of up to 15%.

Studies have found variable impacts on horticultural crops in New Zealand, with a general poleward shift, including an expansion of the area for subtropical crops but a contraction of area suitable for temperate crops such as apples and kiwi fruit that require winter chilling (Salinger *et al.*, 1990). Studies for maize suggest expansion of the suitable growing area into the Canterbury Plains of the South Island (Kenny *et al.*, 1994; Tate *et al.*, 1994; Warrick and Kenny, 1994).

For small island states, fewer studies have been conducted. Singh *et al.* (1990) conclude that, in general, crop yields would be lower because of reduced solar radiation (from increased cloudiness), higher temperature (leading to shorter growth duration and increased sterility), and water availability (both drought and inundation). Sea water intrusion also could affect some coastal areas. Some of the negative effects, particularly

Table 13-7: Selected studies for Australia and New Zealand.

Study	Scenario	Geographic Scope	Crops	Yield Impact (%)	Other Comments
Campbell, 1994; Campbell <i>et al.</i> , 1995; Newton <i>et al.</i> , in press	Various	New Zealand	Pasture	increase overall, but decrease in some regions	GCM scenarios and climate sensitivity result in yield increases w/ and w/o CO ₂ fertilization; increases of up to 15% w/ CO ₂ fertilization; earlier studies found larger increases, but likely overestimated the CO ₂ effect; additional findings include altered seasonality of pasture with effects on livestock management
Salinger <i>et al.</i> , 1990	*	New Zealand	Temperate Crops and Pasture	increase	Crop shifts of 200m in altitude and 200km poleward; earlier crop maturation; longer frost-free season
McKeon <i>et al.</i> , 1988	+2°C, -20% winter precipitation, +30% rest	SW Queensland, Australia	Semi-Arid Perennial Grass, Wheat	+31 (-1, +35) +23 (-6, +35)	Temperature only (precipitation only in parentheses); no CO ₂ effect; for grasslands, increased risk from undesirable shrubs and grasses, animal nutrition and health, and soil erosion; new areas may be available
Vickery <i>et al.</i> , 1993	+2°C, +10 to +20% precip. Nov. to March	Northern NSW, Australia	Cool Temperate Grazing	not assessed	Expansion of high NPP (3.2 to 4.8 t/ha) area from 59 to 64% of the region; soil and landscape as possible limiting factors not considered
Erskine <i>et al.</i> , 1991	GISS, GFDL, UKMO	S. Australia	Wheat	-6 to +13	Included CO ₂ to 555 ppm; results w/o CO ₂ were -15 to -16%; no varietal adaptation or other management change
Wang <i>et al.</i> , 1992	+3°C	Horsham, Victoria, Australia	Wheat	-34 to +65	Included CO ₂ to 700 ppm; range across cultivars; losses occurred for early-maturing varieties and stemmed mainly from shortened vegetative growing period
Russel, 1988	+2 to +4°C	Queensland, Australia	Sugar Cane	+9 to +13	Southward expansion possible; also considered similar temperature declines; yields -40 to -17%

*Used climate scenarios as given in Salinger and Hicks (1990), which are mean changes derived from the results of several GCMs.

of C₃ crops, would be offset by the beneficial effects of elevated CO₂. No quantitative estimates of sensitivities or thresholds directly related to agriculture have been reported in major impact studies (e.g., Hughes and McGregor, 1990; Pernetta and Hughes, 1990; Hay and Kaluwin, 1992).

Singh (1994) considers the vulnerability of small island nations to some large changes in climatic conditions that, while not currently predicted by climate models, indicate sensitivities. Increasing aridity (reductions in rainfall and prolonged dry seasons) affecting small islands and the leeward side of bigger islands was estimated to result in general crop failure, migration of human populations, wind erosion, and negative impacts on wildlife. A somewhat less severe drying (prolonging the dry season by 45 days or more) would decrease yields of maize (30 to 50%), sugar cane (10 to 35%), and taro (35 to 75%). Singh (1994) also found that significantly increased rainfall (+50%) during the wet season on the windward side of large islands, while increasing yields of taro

(5 to 15%), would reduce yields of rice (10 to 20%) and severely reduce maize yields (30 to 100%). Maize failures from increased precipitation stem from inundation, and rice yield losses stem from increased cloudiness (reduced solar irradiation).

13.6.5. Areas of the Former USSR

Climate impact studies conducted over the past 15 years include those of Zhukovsky and Belechenko (1988), Zhukovsky *et al.* (1992), and Sirotenko *et al.* (1984). These studies did not include the direct effect of increasing atmospheric CO₂. Recent estimates have included coverage of most of the region and have included the CO₂ effect (Menzhulin and Koval, 1994) and other environmental change (Sirotenko and Abashina, 1994; Sirotenko *et al.*, 1991). These new studies also have been the first conducted for this region based on climate scenarios drawn from GCM runs (Table 13-8).

Table 13-8: Selected crop studies for Russia and the former Soviet republics.

Study	Scenario	Geographic Scope	Crop(s)	Yield Impact (%)	Other Comments
Menzhulin and Koval, 1994	GISS, GFDL, UKMO	Russia and Former Soviet Republics	Winter and Spring Wheat	-19 to +41	Included CO ₂ effect; GISS strongly positive, UKMO negative; temperature sensitivity alone of 2 and 4°C resulted in yield losses of 20 to 30%; impacts also varied widely across the 19 sites studied
Sirotenko and Abashina, 1994; Sirotenko <i>et al.</i> , 1991 ¹	EMI	Russia	Crop Yield, Grassland Productivity	+10 to +35 -2 to +26	Large positive effect in Southern Volga and Northern Caucasus areas; slightly negative crop yield in S. Krasnoyarsky and Far East; range is w/ and w/o +20% CO ₂ , +30% tropospheric ozone, and -20% soil humus
	CCC, GFDL		Crop Yield, Grassland Productivity	-14 to +13 -27 to -2	

¹These studies used a reconstructed Eemian Interglacial (EMI) climate and the Canadian Climate Centre (CCC) and Geophysical Fluid Dynamics Laboratory (GFDL) GCMs. The temperature and precipitation predictions of the GCMs were scaled by the factors 0.51 (CCC) and 0.45 (GFDL) to generate climates that could be observed by the year 2030.

Sirotenko and Abashina (1994) and Sirotenko *et al.* (1991) scaled the equilibrium temperature and precipitation derived from GCMs to generate scenarios applicable to the year 2030 and used the Eemian interglacial period (EMI) climate. In the EMI scenario, warming was greatest in January and precipitation increased substantially in both January and July, whereas the GCM scenarios suggested drier and warmer summer conditions. Changes in potential crop yield and potential productivity of grasses are based on a geoinformation system CLIMATE-SOIL-YIELD and a dynamic-growth crop simulation model (Sirotenko, 1981; Abashina and Sirotenko, 1986; Sirotenko, 1991) (Table 13-8). The results indicate that the climate response of crops and grasses can differ even in sign.

The estimated response of agriculture varied significantly across the region as well as across climate scenarios. Sirotenko and Abashina (1994) and Sirotenko *et al.* (1991) estimate the impacts to be favorable on agriculture of the northern areas of European Russia and Siberia and to cause a general northward shift of crop zones. Actual changes in production would reflect both areal expansion and the yield changes on existing crop areas as reported in Table 13-8. The more arid climate of the Canadian Climate Centre (CCC) and Geophysical Fluid Dynamics Laboratory (GFDL) GCMs was projected to have severe effects on grain production in the steppes of Povolzhye, Northern Caucasus, and the southern portion of Western Siberia, where grain production was estimated to fall by 20–25%. Menzhulin and Koval (1994) simulated yield increases exceeding 50% in the northwestern, central, and eastern regions of Kazakhstan under the GISS scenario, primarily because of increased moisture in these currently arid areas, but these areas did not benefit substantially under the GFDL scenario. Overall, the UK Meteorological Office (UKMO) scenario produced the largest yield declines.

Sirotenko and Abashina (1994) and Sirotenko *et al.* (1991) found that potential increases in ozone and loss of soil organic

matter reduced potential yields substantially; when combined with the climate/CO₂ scenarios, grass yields declined by about one-quarter and crop yields by 10% in both CCC and GFDL GCM scenarios. Kovda and Pachepsky (1989) report the potential for significant additional soil loss and degradation resulting from climate change.

Historically, climate variability has been a significant contributor to yield variability in areas of the former USSR. For example, the increase in aridity during the 1930s was estimated to have decreased yields by 25–39% (Menzhulin, 1992). If drier conditions prevail under climate change, similar yield effects may occur.

13.6.6. Latin America

Climate impact studies for Latin America that include the direct effect of CO₂ generally show negative impacts for wheat, barley, and maize but positive impacts for soybeans (Table 13-9). A study of Norte Chico, Chile, suggested decreased yields for wheat and grapes but increases for maize and potatoes (Downing, 1992). The Norte Chico results are difficult to generalize because the climate for Chile exhibits steep temperature gradients from east to west due to the change in altitude, as well as wide variation from north to south.

The largest area with clear vulnerability to climate variability in the region is the Brazilian northeast. Like most agricultural areas of Latin America, this region has a rainy season when crops are grown and a dry season with little or no rain. In the case of the Brazilian northeast, the rainy season is relatively short (3–4 months) and the occurrence of years with no rainy season is frequent. These years are characterized by the occurrence of famine and large-scale migrations to metropolitan areas. Climatic variations that would result in shorter rainy seasons and/or increased

Table 13-9: Selected crop studies for Latin America.

Study	Scenario	Geographic Scope	Crop(s)	Yield Impact (%)	Other Comments
Baethgen, 1992, 1994	GISS, GFDL, UKMO ¹	Uruguay	Barley Wheat	-40 to -30 -30	w/ and w/o CO ₂ ; with adaptation, losses were 15 to 35%; results indicate increased variability
Baethgen and Magrin, 1994	UKMO	Argentina	Wheat	-10 to -5	w/ CO ₂ ; high response to CO ₂ , high response to precipitation
Siquera <i>et al.</i> , 1994; Siquera, 1992	GISS, GFDL, UKMO ¹	Brazil	Wheat Maize Soybean	-50 to -15 -25 to -2 -10 to +40	w/ CO ₂ , w/o adaptation; adaptation scenarios did not fully compensate for yield losses; regional variation in response
Liverman <i>et al.</i> , 1991, 1994	GISS, GFDL, UKMO ¹	Mexico	Maize	-61 to -6	w/ CO ₂ ; adaptation only partly mitigated losses
Downing, 1992	+3°C, -25% precip.	Norte Chico, Chile	Wheat Maize Potatoes Grapes	decrease increase increase decrease	The area is especially difficult to assess because of the large range of climates within a small area
Sala and Paruelo, 1992, 1994	GISS, GFDL, UKMO ¹	Argentina	Maize	-36 to -17	w/ and w/o CO ₂ ; better adapted varieties could mitigate most losses

¹These studies also considered yield sensitivity to +2 and +4°C and -20 and +20% change in precipitation.

frequency of rainless years would have extremely negative consequences for the region.

13.6.7. Western Europe

Simulated yields of grains and other crops have been generally found to increase with warming in the north, particularly when adaptation is considered, but decrease substantially in the Mediterranean area even with adaptation (Table 13-10). Northern yield increases depend on the beneficial effects of CO₂ on crop growth and climate scenarios showing sufficient increases in precipitation to counter higher rates of evapotranspiration. Yield declines in the Mediterranean region are due to increased drought resulting from the combination of increased temperature and precipitation decreases (or insufficient increases to counter higher evapotranspiration).

For many vegetable crops, warmer temperatures will generally be beneficial, with the options and possibilities for vegetable production generally expanding in northern and western areas. For cool-season vegetable crops such as cauliflower, larger temperature increases may reduce the number of plantings possible during cooler portions of the year or decrease production, particularly in southern Europe (Kenny *et al.*, 1993; Olesen and Grevsen, 1993). Decreased yield quality is also possible, with the effect most pronounced in southern Europe.

Warmer winters will reduce winter chilling and probably adversely affect apple production in temperate maritime areas, and could lead to loss of adequate winter chilling for crops such as peaches, nectarines, and kiwi fruit in southern Europe.

Significant shifts in areas suitable for different types of grapes also could occur (Kenny and Harrison, 1992).

Among other effects, warming implies reduction in greenhouse costs for horticultural production. However, increased infestations of pests such as the Colorado beetle on potatoes and rhizomania on sugar beet may result from higher temperatures.

Studies have investigated changes in crop potential evapotranspiration (PET) (Le Houerou, 1994; Rowntree, 1990), finding that under higher temperatures the crop growing season would be extended for grain crops, assuming an increase in the number of frost-free days. For southern Europe, the extension of the growing season would likely be insufficient to avoid high summer temperatures by planting earlier. Thus, reduced grain filling period and lower yields are likely. Other studies have explored how the climatically limited range for crops, including maize, wheat, cauliflower, and grapes, would change under various GCMs and other climate scenarios (Carter *et al.*, 1991a, 1991b; Parry *et al.*, 1992; Kenny *et al.*, 1993; Kenny and Harrison, 1993; Wolf, 1993a, 1993b). In general, these studies found a northward shift of crop-growing zones with potential for grain maize to be grown as far north as the UK and central Finland. Increased demand for irrigation and/or increased areas likely to suffer from water deficits, particularly in southern Europe, also were found.

13.6.8. USA and Canada

Studies listed in Tables 13-11 (USA) and 13-12 (Canada) show a wide range of impacts. Much of the wide variation reflects

differences among sites. Effects are more likely negative or more severely negative for southern areas and for climate scenarios such as the UKMO GCM scenario in which the temperature increases are large (+5.2°C) or the GFDL scenario in which summer aridity increased.

Rosenzweig (1985) simulated increased areas for wheat production, especially in Canada, under the GISS climate change scenario, while major wheat regions in the United States remain the same (Rosenzweig, 1985). Crosson (1989) found that warmer temperatures may shift much of the wheat-maize-soybean producing capacity northward, reducing U.S. production and increasing production in Canada. Shifting climate zones may result in lower production of corn or wheat and different and more diverse crops because the productivity in the new areas is likely to be limited due to the shallow, infertile soils (CAST, 1992).

Across studies in Table 13-11 for the USA that combined biophysical and economic impacts, market adjustments lessen the

impacts of negative yield changes. Different assumptions about changes in U.S. population, income, trade barriers, and institutions were found, in some cases, to determine whether the net economic impact of climate change on the USA was negative or positive. Kaiser *et al.* (1993) found that possible increases in agricultural commodity prices could more than offset farm income loss. Mendelsohn *et al.* (1994) used an econometric approach to directly estimate the impact of climate change on agricultural revenue and asset values. This approach more fully considers potential adaptation to different climates as directly observed across climates that vary as a result of geography. They found that for the United States, warming would generally be beneficial even without the direct effect of CO₂. This approach calculates an equilibrium response after complete adjustment and does not consider price changes.

A number of studies have considered the vulnerability of prairie agriculture to climate change in Canada (Cohen *et al.*, 1992). Factors cited as contributing to vulnerability include the

Table 13-10: Selected crop studies for Western Europe.

Study	Scenario	Geographic Scope	Crop(s)	Yield Impact (%)	Other Comments
Oleson <i>et al.</i> , 1993	*	Northern Europe	Cauliflower	increase	Quality affected by temperature; longer season
Goudriaan and Unsworth, 1990	+3°C	Northern Europe	Maize (fodder)	increase	Shift to grain production possible
Squire and Unsworth, 1988	+3°C	Northern Europe	Wheat	increase	
Kettunen <i>et al.</i> , 1990	GCMs	Finland	Potential Yield	+10 to +20	Range is across GISS and UKMO GCMs
Rötter and van Diepen, 1994	+2°C (winter), +1.5°C (summer)	Rhine Area	Cereals, Sugar Beet, Potato, Grass	+10 to +30	Also +10% winter precipitation; includes direct effect of CO ₂ ; range is across crop, agroclimatic zone, and soil type; decreased evapotranspiration (1 to 12%), except for grass
UK Dept. of Environment, 1992	GCMs +1, +2°C	UK	Grain Horticulture	increase or level increase	Increased pest damage; lower risk of crop failure
Wheeler <i>et al.</i> , 1993	*	UK	Lettuce	level	Quality affected; more crops per season possible
Semonov <i>et al.</i> , 1993	*	UK	Wheat	increase or decrease	Yield varies by region; UKMO scenario negative; includes adaptation and CO ₂
Delecolle <i>et al.</i> , 1994	GCMs** +2, +4°C	France	Wheat	increase or level	Northward shift; w/ adaptation, w/ CO ₂ ; GISS, GFDL, and UKMO GCMs
Iglesias and Minguez, 1993	GCMs**	Spain	Maize	-30 to -8	w/ adaptation, w/ CO ₂ ; irrigation efficiency loss; see also Minguez and Iglesias, 1994
Santer, 1985	+4°C	Italy/Greece	Biomass	-5 to +36	Scenarios also included -10% precipitation
Bindi <i>et al.</i> , 1993	+2, +4°C and *	Italy	Winter Wheat	not estimated	Crop growth duration decreases; adaptation (using slower developing varieties) possible

* Climate scenarios included GISS, GFDL, and UKMO and time-dependent scenarios, using GCM methodology, based on emission scenarios proposed by the IPCC in 1990. Composite scenarios for temperature and precipitation were based on seven GCMs and scaled by the global-mean temperature changes associated with the IPCC 1990 emission scenarios for the years 2010, 2030, and 2050 (Barrow, 1993).

** These studies also considered yield sensitivity to +2 and +4°C and -20 and +20% change in precipitation.

prairie's importance as an agricultural producer, located in a marginal climate, constrained by both temperature and precipitation; soil limitations that limit shifting of cropping northward; known sensitivity to climate as evidenced by past drought experiences; and vulnerability to midcontinental drying indicated by GCMs. The effects of the 1988 drought are an indication of the region's sensitivity to climate variability. The effects included dust storms and wind erosion, production declines of 29% (grains) to 94% (hay), falling grain inventories, higher prices, poor pastures for livestock with some movement of cattle to moister areas, higher feed costs for livestock, and farm income reductions of 50% to 78% compared to 1987 figures.

13.7. Regional Summary: Relative Vulnerability

There has been a substantial number of new agricultural impact studies since the 1990 IPCC and the 1992 update, as reviewed

in Section 13.6. For countries in sub-Saharan Africa, the Middle East and North Africa, Eastern Europe, and Latin America, however, there are still relatively few studies. For most regions, studies have focused on one or two principal grains. These studies strongly demonstrate the variability in estimated yield impacts among countries, scenarios, methods of analysis, and crops, making it difficult to generalize results across areas or for different climate scenarios. Thus, the ability to extend, interpolate, or extrapolate from the specific climate scenarios used in these studies to "more" or "less" climate change is limited.

Given these uncertainties in both magnitude and direction of impact, a key issue is *vulnerability* to possible climate change. Vulnerability is used here to mean the *potential* for negative consequences that are difficult to ameliorate through adaptive measures given the range of possible climate changes that might reasonably occur. Defining an area or population as vulnerable,

Table 13-11: Selected U.S. agricultural impact studies.

Study	Scenario	Geographic Scope	Crops	Yield Impact (%)	Other Comments
Adams <i>et al.</i> , 1988, 1990, 1994	GCMs ¹	U.S.	All	increase and decrease	Results vary across GISS, GFDL, and UKMO climates and regions; generally positive for 2°C and negative for 4°C; net economic effects depend on exports and CO ₂ effects; increased irrigation; adaptation mitigates losses
Cooter, 1990	GISS	South	Maize	decrease	Potential risk of aquifer contamination
Easterling	1930s	Missouri,	Maize	-23 to -6	More severe effect w/o CO ₂ or adaptation;
<i>et al.</i> , 1993	analog	Iowa,	Sorghum	-20 to +26	less severe or increase w/ CO ₂ and adaptation
		Nebraska,	Wheat	-11 to +17	
		Kansas	Soybean	-26 to +2	
			Alfalfa	-5 to +22	
Kaiser <i>et al.</i> , 1993, 1994	Mild, severe	Central and southeast states, Minnesota, Nebraska	Maize Wheat Sorghum Soybean	increase and decrease	Climate scenarios included +2.5°C/+10% precipitation and +4.2°C/+20% precipitation; economic adaptation included; northern states less affected; results vary by crop/scenario
Mendelsohn <i>et al.</i> , 1994	+2.5°C, +8% precip.	U.S. county level	All	not estimated	Positive effect on crop revenue after long-run adjustment when considering revenue shares as weights that give greater importance to vegetables, fruits, etc.
Mearns <i>et al.</i> , 1992a, 1992b	GISS	Kansas	Wheat	increased variability and crop failure	Precipitation more important than temperature in scenarios, except for GISS
Muchow and Sinclair, 1991		Illinois	Grains	increase or slight decrease	Most sensitive to precipitation changes
Rosenzweig <i>et al.</i> , 1994	GISS, GFDL, UKMO*	Southeast U.S., Great Lakes U.S. sites	Soybean Maize Wheat	-96 to +58 -55 to +62 -100 to +180	w/ CO ₂ effect; UKMO scenario, southern sites more severely affected; average for total USA assessed for wheat (-20 to -2%), maize (-30 to -15%), and soybeans (-40 to +15%); Peart <i>et al.</i> (1989), Ritchie <i>et al.</i> (1989), and Rosenzweig (1990) are similar studies

¹These studies also considered yield sensitivity to +2 and +4°C and -20 and +20% change in precipitation.

therefore, is not a prediction of negative consequences of climate change; it is an indication that, across the range of possible climate changes, there are some climatic outcomes that would lead to relatively more serious consequences for the region than for other regions.

Vulnerability depends on the unit of observation and the geographic scale considered. *Yields* are relatively more vulnerable if a small change in climate results in a large change in yield. Evidence suggests that yields of crops grown at the margin of their climatic range or in climates where temperature or precipitation could easily exceed threshold values during critical crop growth periods are more vulnerable (e.g., rice sterility: Matthews *et al.*, 1994a, 1994b).

Farmer or farm sector vulnerability is measured in terms of impact on profitability or viability of the farming system. Farmers with limited financial resources and farming systems with few adaptive technological opportunities available to limit or reverse adverse climate change may suffer significant disruption and financial loss for relatively small changes in crop yields and productivity. For example, semi-arid, cool temperate, and cold agricultural areas may be more vulnerable to climate change and climate variability (Parry *et al.*, 1988).

Regional economic vulnerability reflects the sensitivity of the regional or national economy to farm sector impacts. A regional economy that offers only limited employment alternatives for workers dislocated by the changing profitability of farming is relatively more vulnerable than those that are economically

diverse. For example, the Great Plains is one of the U.S. regions most dependent on agriculture, and thus might be the most economically vulnerable to climate change (Rosenberg, 1993).

Hunger vulnerability is an “aggregate measure of the factors that influence exposure to hunger and predisposition to its consequences” involving “interactions of climate change, resource constraints, population growth, and economic development” (Downing, 1992; Bohle *et al.*, 1994). Downing (1992) concluded that the semi-extensive farming zone, on the margin of more intensive land uses, appears to be particularly sensitive to small changes in climate. Socioeconomic groups in such areas, already vulnerable in terms of self-sufficiency and food security, could be further marginalized.

These different concepts of vulnerability include different scales of impact—from crop to individual farmer to food markets to the general economy. Given these various definitions and scales of impact, there are people vulnerable to climate change in most regions. Key characteristics of each of the regions help to suggest those more likely to have vulnerable populations (Table 13-13).

By most measures, many of the populations in sub-Saharan Africa appear most vulnerable. The region is already hot, and large areas are arid or semi-arid; average per capita income is among the lowest in the world and has been declining since 1980; more than 60% of the population depends directly on agriculture; and agriculture is generally more than 30% of gross domestic product (GDP). Relatively little of the cropland

Table 13-12: Selected Canadian agricultural impact studies.

Study	Scenario	Geographic Scope	Crop(s)	Yield Impact (%)	Other Comments
Williams <i>et al.</i> , 1988 ¹	GISS84	Saskatchewan	Spring Wheat	-28 to -18	Large interannual fluctuations underlie mean impacts (e.g., -78% yield impact in extreme year); temperature increase of 3°C offset by +40% precipitation
Mooney, 1990 ¹ ; Mooney <i>et al.</i> , 1991 ¹	GISS	Manitoba, Alberta, Saskatchewan	Spring Wheat, Multiple Crops	-36 (Manitoba) negative and positive	Similar for other crops; corn and potatoes increased; precipitation derived from analogous region data; greater crop variety, production area increase
van Kooten ¹	CCC	SW Saskatchewan	Spring Wheat	-15 to +2	Positive effects when CCC precipitation used; negative used current norm for precipitation
Arthur and Abizadeh, 1989 ¹	GISS, GFDL	Alberta, Manitoba, Saskatchewan	Wheat, Oats, Barley, Flax, Canola, Hay	small decrease to +28	10 out of 12 scenarios resulted in gain in net crop revenue; adapt by planting earlier
Brklacich <i>et al.</i> , 1994; Brklacich and Smit, 1992	GISS, GFDL, UKMO ²	Alberta, Manitoba, Saskatchewan, Ontario	Wheat	-40 to +234	Results varied widely by site and scenario; adaptation and CO ₂ were strongly positive effects; Ontario study showed increased net returns, but also variability; N gains and S losses

¹As reported in Cohen *et al.*, 1992.

²These studies also considered yield sensitivity to +2 and +4°C and -20 and +20% change in precipitation.

is irrigated, and much of the agricultural land is used for grazing. Severe famine and starvation have been more prevalent in sub-Saharan Africa than in other regions over recent decades. Political and civil instability have greatly worsened problems. The potential for continued instability is an additional factor that increases vulnerability.

Populations in South Asia are vulnerable because of heavy dependence on agriculture and high population density. Agriculture accounts for more than 30% of GDP in most countries in the region. Each hectare of cropland supports 5.4 people. Tropical storms are an important feature of the climate around which current systems operate. These storms can be destructive but also are the main source of moisture. Changes in their frequency or severity would have significant impacts.

The area is already intensely cropped, with 44% of the land area used as cropland. An estimated 31% of cropland is already irrigated, which may reduce vulnerability somewhat, providing water resources remain adequate. An additional factor that may reduce vulnerability in the future is the relative strength of the economy over the past decade. Countries in this area also have been relatively successful in avoiding the more severe effects of food shortages through programs that ensure access to food during potential famine situations. Chronic hunger remains a problem, however, for the poorer segments of the population, particularly in semi-arid and arid parts of the region.

Within East Asia, populations in the more arid areas of China appear most vulnerable to the possibility of mid-latitude continental drying. In general, the region supports a large population

Table 13-13: Basic regional agricultural indicators.

	Sub-Saharan Africa	Middle East/ N. Africa	South Asia	SE Asia	East Asia	Oceania	Former USSR	Europe	Latin America	USA, Canada
Agric. Land (%) ¹	41	27	55	36	51	57	27	47	36	27
Cropland (%) ¹	7	7	44	13	11	6	10	29	7	13
Irrigated (%) ¹	5	21	31	21	11	4	9	12	10	8
Land Area (10 ⁶ ha)	2390	1167	478	615	993	845	2227	473	2052	1839
Climate	tropical; arid, humid	subtropical, tropical; arid	tropical, subtropical; humid, arid	tropical; humid	subtropical, temp. oceanic, continental; humid	tropical, temp. oceanic, subtropical; arid, humid	polar, continental, temp. oceanic; humid, arid	temp. oceanic, some sub-tropical; humid, arid	tropical, subtropical; mostly humid	continental, subtropical, polar, temp. oceanic; humid, arid.
Pop. (10 ⁶)	566	287	1145	451	1333	27	289	510	447	277
Agric. Pop. (%)	62	32	63	49	59	17	13	8	27	3
Pop/ha Cropland	3.6	3.4	5.4	5.7	12.6	0.5	1.3	3.7	2.9	1.2
Agric. Prod. (10⁶t)										
Cereals	57	79	258	130	433	24	180	255	111	388
Roots and Tubers	111	12.5	26	50	159	3	65	79	45	22
Pulses	5.7	4.1	14.4	2.5	6.3	2	6	7	5.8	2.2
S. Cane and Beet	60	39	297	181	103	32	62	144	494	56
Meat	6.7	5.5	5.7	6.4	39.6	4.5	17	42	20.5	33.5
GNP/Cap. ²	350	1940	320	930	590	13780	2700	15300	2390	22100
Annual Growth ²	-1.2	-2.4	3.1	3.9	7.1	1.5	N/A	2.2	-0.3	1.7
Ag. (% of GDP) ²	>30	10–19	>30	20–>30	20–29	<6	10–29	<6	10–19	<6

¹Agricultural land includes grazing and cropland, reported as a percent of total land area. Cropland is reported as a percent of agricultural land. Irrigated area is reported as a percent of cropland.

²GNP is in 1991 U.S.\$; annual growth (%/annum) is for the period 1980–1991.

Source: Computed from data from FAO Statistics Division (1992); GNP per capita, GNP growth rates, and agriculture as a share of the economy are from World Bank, *World Development Indicators 1993*, and temperature and climate classes from Rötter *et al.*, 1995. Note: East Asia GNP excludes Japan. Also, regional GNP data generally include only those countries for which data are given in Table 1 in *World Development Indicators*. Countries with more than 4 million population for which GNP data are not available include Vietnam, Democratic Republic of Korea, Afghanistan, Cuba, Iraq, Myanmar, Cambodia, Zaire, Somalia, Libya, and Angola; land areas are in hectares, production is in metric tonnes.

per hectare of cropland (12.6). The rapid economic growth achieved over the past decade, the fact that the region's climate is somewhat cooler, and the diverse sources of food production reduce vulnerability of populations in this region. Japan's GNP provides it with significant capability to limit climatic losses from agriculture compared with other countries in the region.

Southeast Asia combines tropical temperatures with generally ample moisture, but the region is subject to tropical storms. The region supports a large population with a relatively high population density per hectare of cultivated land. For several countries in this region, agriculture contributes more than 30% of GDP. GNP per capita is somewhat higher than that of either South or East Asia, and growth has been substantial over the past decade. However, Table 13-13 excludes several countries in the region due to lack of data. These countries, including Vietnam, Cambodia, and Myanmar, have relatively large populations, and their economic performance has been poorer than others in the region. Populations in these countries may be particularly vulnerable to changes in tropical storms.

The Middle East and North Africa are already very hot and generally arid. The current climate greatly limits the portion of land currently suitable for agriculture. A large share of current cropland is irrigated. Among developing country areas, a relatively smaller share of the population (32%) depends directly on agriculture. Agriculture is quite diverse; fruits, vegetables, and other specialty crops are important. The region is heterogeneous, including relatively wealthy oil-exporting countries, Israel, and several poorer countries—making the regional average economic performance somewhat misleading. Per capita GNP has fallen substantially over the past decade, with declining oil prices and political disruptions partly responsible.

Latin America and countries that now make up the area that was formerly the USSR are similar in terms of per capita GNP. While data are unavailable with regard to economic performance for the area of the former USSR, evidence strongly suggests that the region suffered a decline in per capita GNP over the past decade, as has Latin America. The two regions are also similar in that average population density and population per hectare of cropland are moderate to low. Estimates of potential additional cropland for the world suggest that these two areas could be the source of substantial additional cropland (Crosson, 1995). Thus, expansion of land area or relocation to adapt to climate change is a possible response, partly mitigating vulnerability. The prevalence of childhood malnutrition, infant mortality, and low median age at death are somewhat higher in Latin America than in the area of the former USSR (World Bank, 1993). While both regions are primarily humid, substantial agricultural areas are arid or semi-arid and drought-prone. The notable difference between the two regions is that Latin America is generally already tropical or subtropical, and even though GCMs predict less warming in the tropics, further warming may be deleterious. In contrast, agriculture in large areas of the former USSR is limited by cool temperatures and so may benefit from warming. Arid areas of tropical Latin America, such as northwest Brazil, are

particularly vulnerable to changes in ENSO events if they result in less reliable precipitation.

Europe, the USA and Canada, and Oceania have high GNP per capita, the agricultural population is a small share of the total population, and agriculture is in general a small share of the economy. As a result, vulnerability to climate-change-induced hunger or severe economic distress for the overall economy is relatively low. These areas are important for world food production. Mid-continental areas of the U.S. and Canada, the Mediterranean area of Europe, and large areas of Australia are prone to drought, which would be exacerbated if climate change reduced moisture availability or increased the demand for water as occurs in several GCM scenarios. Economic dislocation is likely to be limited to the agricultural sector or to subregions highly dependent on agriculture.

Small island nations, especially where incomes are low, are subject to particular vulnerabilities. Potential loss of coastal land to sea level rise, salt water intrusion into water supplies, damage from tropical storms, and temperature and precipitation change will combine to affect the agriculture of island nations. Sea water inundation and salt water intrusion are not unique to small island nations. However, these problems take on greater importance where coastal area is a high proportion of the total area of the country, alternative sources of fresh water are limited, and the area available for retreat from sea-level rise is limited. Local sources of food are especially important for these countries because transportation costs can be substantial for remote locations with small populations, particularly for highly perishable products. Most attention has been focused on Pacific Island Countries in Oceania, but other island countries such as the Maldives are presented with similar conditions.

13.8. Global Agricultural Issues and Assessments

13.8.1. The Current and Future Agricultural System

Climate change will be only one of many factors that will affect world agriculture. The broader impacts of climate change on world markets, on hunger, and on resource degradation will depend on how agriculture meets the demands of a growing population and threats of further resource degradation. World agriculture has proven in the past to be responsive to the increasing demand for food. Evidence of this is the trend of falling real prices for food commodities (Mitchell and Ingco, 1995, estimated a 78% decline between 1950 and 1992) and the steady growth of worldwide food production over the past 3 decades. Average annual increases were 2.7% per annum during the 1960s, 2.8% during the 1970s, and 2.1% during the 1980s.

Despite global abundance, many countries suffer from disrupted agricultural production and distribution systems, such that famine and chronic hunger are a reality or a distinct threat. While the number of people suffering from chronic hunger has declined (from an estimated 844 million in 1979 to 786 million in 1990; Bongaarts, 1994), the causes of famine are complex,

including a lack of the rights and means to obtain food (employment, adequate income, and a public system for responding to famine) (e.g., Sen, 1981, 1993); political systems disrupted by war and unrest; ineffective or misdirected policies; as well as, or in addition to, drought and other extreme climatic events (McGregor, 1994). The nearly 800 million people still estimated to suffer from chronic hunger and malnutrition represent 20% of the population of developing countries, with the percentage as high as 37% in sub-Saharan countries (FAO, 1995). In many situations of chronic hunger, the population is rural and their livelihood depends primarily on agriculture. However, Kates and Chen (1994a, 1994b), though noting the potential risks of climate change beyond those represented in median cases, provide an array of actions that could be undertaken to achieve a food-secure world.

Agricultural and resource policies have important effects on agricultural production, and national governments have intervened in agriculture in many ways and for various reasons (Hayami and Ruttan, 1985). Many developed countries have subsidized agriculture and thereby encouraged production, while intentionally idling land to control surplus stocks of agricultural commodities. Many developing countries have controlled food prices to benefit lower-income food consumers but have thereby discouraged domestic production. Reduction of trade-distorting government interventions in agriculture was part of the recently concluded round of the General Agreement on Tariffs and Trade (GATT). National policies also greatly affect land use and water use, management, and pricing.

Three major studies of the future world food situation suggest that in the absence of climate change, food supply will continue to expand faster than demand over the next 20 to 30 years, with world prices projected to fall (Alexandratos, 1995; Mitchell and Ingco, 1995; Rosegrant and Agcaoili, 1995). Others are less optimistic, citing limits on further land expansion and irrigation, resource degradation, and reduced confidence that the historical rates of increase in yield will continue (Bongaarts, 1994; McCalla, 1994; Norse, 1994).

Factors that will jointly determine whether agricultural supply increases can keep pace with demand include (1) how fast demand will grow, (2) the future availability of land and its quality, (3) the future availability of water, and (4) whether improvements in technology will continue to result in rapid yield growth. Finally, economic growth and development are closely tied to demand growth and, in many developing countries, are also dependent on agricultural development.

13.8.1.1. Demand Growth

Between 1950 and 1990, world population grew at a 2.25% compound annual rate. Through 2025, population is projected to grow at a compound annual rate of between 1.13% and 1.55% (high and low UN variants). The decade of the 1990s is projected to have the largest absolute population addition, with declining additions in subsequent decades (Bongaarts, 1995).

Thus, food supply growth could slow by 40–50% from recent decades while maintaining per capita food production levels. Income growth likely will cause demand to grow more rapidly than population and will change the composition of demand, most likely away from food grains and toward meat, fruits, and vegetables. The shift to meat is likely to increase the demand for grain for livestock feed. Increased demand generated by increased income growth would allow more and higher-quality food to be consumed per capita (Mitchell and Ingco, 1995), but this depends on how food consumption is distributed. Beyond 2025, population growth is generally projected to be low as world population is projected to stabilize by around 2075.

13.8.1.2. Land Quantity and Quality

Some estimates suggest that there is much potentially available land (Buringh and Dudal, 1987), but the cost of bringing it under production may be high, with attendant adverse environmental impacts limiting expansion (Crosson, 1995). Intensification of production on existing cropland may worsen land degradation and put additional pressure on water and soil resources. Firm data on the extent and severity of land degradation and its impact on production potential for most of the world are not available (El-Swaify *et al.*, 1982; Dregne, 1988; Nelson, 1988; Lal and Okigbo, 1990), but a recent overview (Oldeman *et al.*, 1990), though still qualitative in economic terms, confirms significant degradation and loss of arable land, especially in Africa (see Chapter 4). Studies disagree on the extent to which intensification affects land degradation (Crosson and Stout, 1983; Brown and Thomas, 1990; Tiffen *et al.*, 1993). Competition for agricultural resources for other uses may also affect the supply and price of land for agriculture. Carbon sequestration, biomass energy production, forest product production, the potential development of new non-food agricultural products, and removal of agricultural land from production for other environmental objectives will affect the amount of land available for food production (see Chapters 23, 24, and 25).

13.8.1.3. Water Supply and Irrigation

Irrigation has contributed significantly to increased production in the past. Currently, 17% of global cropland is irrigated, but this 17% of land accounts for more than one-third of total world food production. An estimated additional 137 million hectares have the potential to be irrigated, compared with the 253 million hectares currently irrigated (World Bank, 1990), but the cost of doing so may be prohibitive. Current water systems in many developing countries achieve low efficiencies of water distribution, and average crop yields are well below potential (Yudelman, 1993; Crosson, 1995; Rosegrant and Agcaoili, 1995). There are environmental and health-related effects of irrigation such as soil salinization and the spread of water-borne diseases that may limit further expansion (Brown and Thomas, 1990; Dregne and Chou, 1990; Jensen *et al.*, 1990; Crosson, 1995). Major factors contributing to these irrigation problems in both developing and developed countries

are unpriced and heavily subsidized water resources; inadequate planning, construction, and maintenance of water systems; unassigned water rights or rules that limit the transfer of rights; and conflicts between development and distribution goals (Frederick, 1986; Asian Development Bank, 1991; Moore, 1991; Umali, 1993; Yudelma, 1993; Appendine and Liverman, 1994). Solutions to these problems are available in most cases, and a recent study found that investments in irrigation have been at least as profitable as investments in other agricultural enterprises (World Bank, 1994). Changes in potential irrigation water supply due to climate change have not generally been integrated into agricultural impact studies, with few exceptions (e.g., Rosenberg, 1993). For climatic impacts on water supply, see Chapter 10.

13.8.1.4. Future Yield Growth

Assumed continuation of yield increases due to improving technology and further adoption of existing technologies is uncertain. Gaps between actual and potential yield are cited as evidence of unexploited production potential, but potential yields are rarely, if ever, attained in practice (Tinker, 1985; Plucknett, 1995). Realization of improved varieties depends on continuation of agricultural research and crop breeding systems and the exchange of germplasm (Duvick, 1995).

13.8.1.5. Future Economic Development

The impact of climate change on human populations in terms of famine, chronic hunger, health, and nutrition will depend on how and whether currently poor areas develop over the next 20 to 50 years. The future path of development of currently vulnerable countries remains uncertain. Policy failures, wars, and political and civil unrest are identified causes, but correcting these problems has proved difficult (e.g., van Dijk, 1992; Anand and Ravallion, 1993). Lagging agricultural development has been identified as a consequence of significant policy distortions in many developing countries, conflicting with the industrial sector and limiting the ability of the broader economy to grow (Hayami and Ruttan, 1985; Adelman and Vogel, 1992; Cavallo *et al.*, 1992; FAO, 1995).

13.8.2. Global Climate Impact Studies

Accurate consideration of national and local food supply and economic effects depends on an appraisal of changes in global food supply and prices. International markets can moderate or reinforce local and national changes. In 1988, for example, drought presented a more severe threat because it occurred coincidentally in several of the major grain-growing regions of the world.

While uncertainties continue to exist about the direction of change in global agricultural production resulting from climate change, changes in the aggregate level of production have been

found to be small to moderate (Kane *et al.*, 1992; Fischer *et al.*, 1994; Reilly *et al.*, 1994; Rosenzweig and Parry, 1994). Studies show that a disparity in agricultural impact between developed and developing countries can be reinforced by markets (Tables 13-14, 13-15).

Rosenzweig *et al.* (1994) found that in lower-latitude developing countries, cereal grain crop yields and production declined under climate change scenarios ranging from 2.5 to 5.2°C. The study further found that the population at risk of hunger (defined as a measure of food energy availability, which depends on income and food price levels, relative to nutritional requirements) could increase despite adaptation. The study involved agricultural scientists in 18 countries using comparable crop growth models for wheat, rice, maize, and soybean (IBSNAT, 1989) and consistent climate change scenarios (Rosenzweig and Iglesias, 1994). Estimated yield changes were the basis for supply changes in the Basic Linked System (BLS), a world food trade model (Fischer *et al.*, 1988).

Reilly and Hohman (1993) and Reilly *et al.* (1994) used the same national crop yield changes as Rosenzweig *et al.* (1994) in a different trade model and found that agricultural exporters may gain even though their supplies fall as a result of higher world prices. They found that developing countries did worse in economic

Table 13-14: Change in cereals production under three different GCM equilibrium scenarios (percent from base estimated in 2060).

Region	GISS	GFDL	UKMO
World Total			
Climate effects only	-10.9	-12.1	-19.6
Plus physiological effect of CO ₂	-1.2	-2.8	-7.6
Plus adaptation level 1	0.0	-1.6	-5.2
Plus adaptation level 2	1.1	-0.1	-2.4
Developed Countries			
Climate effects only	-3.9	-10.1	-23.9
Plus physiological effect of CO ₂	11.3	5.2	-3.6
Plus adaptation level 1	14.2	7.9	3.8
Plus adaptation level 2	11.0	3.0	1.8
Developing Countries			
Climate effects only	-16.2	-13.7	-16.3
Plus physiological effect of CO ₂	-11.0	-9.2	-10.9
Plus adaptation level 1	-11.2	-9.2	-12.5
Plus adaptation level 2	-6.6	-5.6	-5.8

Source: Rosenzweig and Parry, 1994.

Notes: Level 1 adaptation included changes in crop variety but not the crop, the planting date of less than 1 month, and the amount of water applied for areas already irrigated.

Level 2 adaptation additionally included changes in the type of crop grown, changes in fertilizer use, changes in the planting date of more than 1 month, and extension of irrigation to previously unirrigated areas.

Table 13-15: Economic effects of three GCM equilibrium scenarios (billions of 1989 U.S.\$).

Region\GCM	With CO ₂ and Adaptation			With CO ₂ , No Adaptation			No CO ₂ , No Adaptation		
	GISS	GFDL	UKMO	GISS	GFDL	UKMO	GISS	GFDL	UKMO
Developing									
<\$500/Cap.	-0.2	-2.6	-14.6	-2.1	-5.3	-19.8	-56.7	-66.1	-121.1
\$500–2000/Cap.	-0.4	-2.9	-10.7	-1.8	-5.1	-15.0	-26.2	-27.9	-48.1
>\$2000/Cap.	-0.6	-0.5	-1.0	-0.8	-0.9	-0.3	-6.7	-4.4	-3.9
Eastern Europe	2.4	0.0	-4.9	1.9	-2.0	-11.0	-12.5	-28.9	-57.5
OECD	5.8	0.0	-6.5	2.7	-3.6	-15.1	-13.5	-21.5	-17.6
TOTAL	7.0	-6.1	-37.6	0.0	-17.0	-61.2	-115.5	-148.6	-248.1

Source: Reilly *et al.*, 1994.

Notes: Measured as annual loss or gain in consumer and producer surplus plus change in society's cost of agricultural policies. Columns may not sum to total due to independent rounding. Adaptation is level 1, as in Table 13-14.

terms as a group, but that some developing countries benefitted. The pattern of winners and losers varied among climate scenarios. Moreover, they found that food-importing countries were found, in some cases, to suffer economic loss because of higher world prices even if the country's crop production potential improved.

Table 13-14 also illustrates how trade and adaptation capability can interact. Developing countries' production levels fell more under adaptation level 1 (small changes in planting dates, changes in cultivars, and additional irrigation water for areas already irrigated) than with no adaptation because their estimated capability to adapt was less than in developed countries. Thus, cereal production in developing countries fell further as trade shifted toward developed-country exports at the expense of developing country production. At adaptation level 2 (substantial changes in planting dates, changes in crop, and extension of irrigation systems), this situation was reversed.

Another global modeling effort considered potential yield and distribution of crops based on a crop suitability index (Cramer and Solomon, 1993; Leemans and Solomon, 1993). Although considering only one climate scenario and omitting the effect of CO₂ fertilization, they found that high-latitude regions uniformly benefited from longer growing periods and increased productivity. Other regions either did not benefit significantly or lost productivity.

More recent work considering global agriculture under climate change found far greater potential for global agriculture to adapt to changing climate than earlier studies (Darwin *et al.*, 1995; reported in Reilly, 1995). This study estimated that climate change alone as represented by equivalent doubled-CO₂ climate scenarios of UKMO, GISS, GFDL, and OSU, without consideration of the direct effects of CO₂, would result in global production losses of less than 1% if no additional land area were devoted to agriculture. If new land area could be brought under cultivation, grain production was estimated to increase on the order of 1%.

13.9. Adaptation

Historically, farming systems have adapted to changing economic conditions, technology, and resource availabilities and have kept pace with a growing population (Rosenberg, 1982; CAST, 1992). Evidence exists that agricultural innovation responds to economic incentives such as factor prices and can relocate geographically (Hyami and Ruttan, 1985; CAST, 1992). A number of studies indicate that adaptation and adjustment will be important to limit losses or to take advantage of improving climatic conditions (e.g., National Academy of Sciences, 1991; Rosenberg, 1992; Rosenberg and Crosson, 1991; CAST, 1992; Mendelsohn *et al.*, 1994).

Despite the successful historical record, questions arise with regard to whether the rate of change of climate and required adaptation would add significantly to the disruption likely due to future changes in economic conditions, technology and resource availabilities (Gommes, 1993; Harvey, 1993; Kane and Reilly, 1993; Smit, 1993; Norse, 1994; Pittock, 1994; Reilly, 1994). If climate change is gradual, it may be a small factor that goes unnoticed by most farmers as they adjust to other more profound changes in agriculture stemming from new technology, increasing demand for food, and other environmental concerns such as pesticide use, water quality, and land preservation. However, some researchers see climate change as a significant addition to future stresses, where adapting to yet another stress such as climate change may be beyond the capability of the system. Part of the divergence in views may be due to different interpretations of adaptation, which include the prevention of loss, tolerating loss, or relocating to avoid loss (Smit, 1993). Moreover, while the technological potential to adapt may exist, the socioeconomic capability to adapt likely differs for different types of agricultural systems (Reilly and Hohmann, 1993).

13.9.1. The Technological Potential to Adapt

Nearly all agricultural impact studies conducted over the past 5 years have considered some technological options for adapting to climate change. Among those that offer promise are:

- **Seasonal Changes and Sowing Dates**—For frost-limited growing areas (i.e., temperate and cold areas), warming could extend the season, allowing planting of longer maturity annual varieties that achieve higher yields (e.g., Le Houerou, 1994; Rowntree, 1990). For short-season crops such as wheat, rice, barley, oats, and many vegetable crops, extension of the growing season may allow more crops per year, fall planting, or, where warming leads to regular summer highs above critical thresholds, a split season with a short summer fallow. For subtropical and tropical areas where growing season is limited by precipitation or where the cropping already occurs throughout the year, the ability to extend the growing season may be more limited and depends on how precipitation patterns change. A study for Thailand found yield losses in the warmer season partially offset by gains in the cooler season (Parry *et al.*, 1992).
- **Different Crop Variety or Species**—For most major crops, varieties exist with a wide range of maturities and climatic tolerances. For example, Matthews *et al.* (1994) identified wide genetic variability among rice varieties as a reasonably easy response to spikelet sterility in rice that occurred in simulations for South and Southeast Asia. Studies in Australia showed that responses to climate change are strongly cultivar-dependent (Wang *et al.*, 1992). Longer-season cultivars were shown to provide a steadier yield under more variable conditions (Connor and Wang, 1993). In general, such changes may lead to higher yields or may only partly offset losses in yields or profitability. Crop diversification in Canada (Cohen *et al.*, 1992) and in China (Hulme *et al.*, 1992) has been identified as an adaptive response.
- **New Crop Varieties**—The genetic base is broad for most crops but limited for some (e.g., kiwi fruit). A study by Easterling *et al.* (1993) explored how hypothetical new varieties would respond to climate change (also reported in McKenney *et al.*, 1992). Heat, drought, and pest resistance; salt tolerance; and general improvements in crop yield and quality would be beneficial (Smit, 1993). Genetic engineering and gene mapping offer the potential for introducing a wider range of traits. Difficulty in assuring that traits are efficaciously expressed in the full plant, consumer concerns, profitability, and regulatory hurdles have slowed the introduction of genetically engineered varieties compared with early estimates (Reilly, 1989; Caswell *et al.*, 1994).
- **Water Supply and Irrigation Systems**—Across studies, irrigated agriculture in general is less negatively affected than dryland agriculture, but adding irrigation is costly and subject to the availability of water supplies. Climate change will affect future water supplies (see Chapter 10). There is wide scope for enhancing irrigation efficiency through adoption of drip irrigation systems and other water-conserving technologies (FAO, 1989, 1990), but successful adoption will require substantial changes in how irrigation systems are managed and how water resources are priced. Because inadequate water systems are responsible for current problems of land degradation, and because competition for water is likely to increase, there likely will be a need for changes in the management and pricing of water regardless of whether and how climate changes (Vaux, 1990, 1991; World Bank, 1994). Tillage method and incorporation of crop residues are other means of increasing the useful water supply for cropping.
- **Other Inputs and Management Adjustments**—Added nitrogen and other fertilizers would likely be necessary to take full advantage of the CO₂ effect. Where high levels of nitrogen are applied, nitrogen not used by the crop may be leached into the groundwater, run off into surface water, or be released from the soil as nitrous oxide. Additional nitrogen in ground and surface water has been linked to health effects in humans and affects aquatic ecosystems. Studies also have considered a wider range of adjustments in tillage, grain drying, and other field operations (Kaiser *et al.*, 1993; Smit, 1993).
- **Tillage**—Minimum and reduced tillage technologies, in combination with planting of cover crops and green manure crops, offer substantial possibilities to reverse existing soil organic matter, soil erosion, and nutrient loss, and to combat potential further losses due to climate change (Rasmussen and Collins, 1991; Logan, 1991; Edwards *et al.*, 1992; Langdale *et al.*, 1992; Peterson *et al.*, 1993; Brinkman and Sombroek, 1993; see also Chapter 23). Reduced and minimum tillage techniques have spread widely in some countries but are more limited in other regions. There is considerable current interest in transferring these techniques to other regions (Cameron and Oram, 1994).
- **Improved Short-Term Climate Prediction**—Linking agricultural management to seasonal climate predictions (currently largely based on ENSO), where such predictions can be made with reliability, can allow management to adapt incrementally to climate change. Management/climate predictor links are an important and growing part of agricultural extension in both developed and developing countries (McKeon *et al.*, 1990, 1993; Nichols and Wong, 1990).

13.9.2. The Socioeconomic Capability to Adapt

While identifying many specific technological adaptation options, Smit (1993) concluded that necessary research on their cost and ease of adoption had not yet been conducted.

One measure of the potential for adaptation is to consider the historical record on past speeds of adoption of new technologies (Table 13-16). Adoption of new or different technologies depends on many factors: economic incentives, varying resource and climatic conditions, the existence of other technologies (e.g., transportation systems and markets), the availability of information, and the remaining economic life of equipment and structures (e.g., dams and water supply systems).

Specific technologies only can provide a successful adaptive response if they are adopted in appropriate situations. A variety of issues has been considered, including land-use planning, watershed management, disaster vulnerability assessment, port and rail adequacy, trade policy, and the various programs countries use to encourage or control production, limit food prices, and manage resource inputs to agriculture (CAST, 1992; OTA, 1993; Smit, 1993; Reilly *et al.*, 1994; Singh, 1994). For example, studies suggest that current agricultural institutions and policies in the United States may discourage farm management adaptation strategies, such as altering crop mix, by supporting prices of crops not well-suited to a changing climate, providing disaster payments when crops fail, or prohibiting imports through import quotas (Lewandowski and Brazee, 1993).

Existing gaps between best yields and the average farm yields remain unexplained, but many are due in part to socioeconomic considerations (Oram and Hojjati, 1995; Bumb, 1995); this adds considerable uncertainty to estimates of the potential for adaptation, particularly in developing countries. For example,

Table 13-16: *Speed of adoption for major adaptation measures.*

Adaptation	Adjustment Time (years)	Reference
Variety Adoption	3–14	Dalrymple, 1986; Griliches, 1957; Plucknett <i>et al.</i> , 1987; CIMMYT, 1991; Wang <i>et al.</i> , 1992
Dams and Irrigation	50–100	James and Lee, 1971; Howe, 1971
Variety Development	8–15	Plucknett <i>et al.</i> , 1987; Knudson, 1988
Tillage Systems	10–12	Hill <i>et al.</i> , 1994; Dickey <i>et al.</i> , 1987; Schertz, 1988
New Crop Adoption: Soybeans	15–30	FAO, Agrostat (various years)
Opening New Lands	3–10	Medvedev, 1987; Plusquellec, 1990
Irrigation Equipment	20–25	Turner and Anderson, 1980
Transportation System	3–5	World Bank, 1994
Fertilizer Adoption	10	Pieri, 1992; Thompson and Wan, 1992

Baethgen (1994) found that a better selection of wheat variety combined with an improved fertilizer regime could double yields achieved at a site in Uruguay to 6 T/ha under the current climate with current management practices. Under the UKMO climate scenario, yields fell to 5 T/ha—still well above 2.5–3.0 T/ha currently achieved by farmers in the area. On the other hand, Singh (1994) concludes that the normal need to plan for storms and extreme weather events in Pacific island nations creates significant resiliency. Whether technologies meet the self-described needs of peasant farmers is critical in their adaptation (Cáceres, 1993). Other studies document how individuals cope with environmental disasters, identifying how strongly political, economic, and ethnic factors interact to facilitate or prevent coping in cases ranging from the Dust Bowl disaster in the United States to floods in Bangladesh to famines in the Sudan, Ethiopia, and Mozambique (McGregor, 1994). These considerations indicate the need for local capability to develop and evaluate potential adaptations that fit changing conditions (COSEPUP, 1992). Important strategies for improving the ability of agriculture to respond to diverse demands and pressures, drawn from past efforts to transfer technology and provide assistance for agricultural development, include:

- Improved training and general education of populations dependent on agriculture, particularly in countries where education of rural workers is currently limited. Agronomic experts can provide guidance on possible strategies and technologies that may be effective. Farmers must evaluate and compare these options to find those appropriate to their needs and the circumstances of their farms.
- Identification of the present vulnerabilities of agricultural systems, causes of resource degradation, and existing systems that are resilient and sustainable. Strategies that are effective in dealing with current climate variability and resource degradation also are likely to increase resilience and adaptability to future climate change.
- Agricultural research centers and experiment stations can examine the “robustness” of present farming systems (i.e., their resilience to extremes of heat, cold, frost, water shortage, pest damage, and other factors) and test the robustness of new farming strategies as they are developed to meet changes in climate, technology, prices, costs, and other factors.
- Interactive communication that brings research results to farmers—and farmers’ problems, perspectives, and successes to researchers—is an essential part of the agricultural research system.
- Agricultural research provides a foundation for adaptation. Genetic variability for most major crops is wide relative to projected climate change. Preservation and effective use of this genetic material would provide the basis for new variety development. Continually changing climate is likely to increase the value of networks of experiment stations that can share genetic material and research results.

- Food programs and other social security programs would provide insurance against local supply changes. International famine and hunger programs need to be considered with respect to their adequacy.
- Transportation, distribution, and market integration provide the infrastructure to supply food during crop shortfalls that might be induced in some regions because of climate variability or worsening of agricultural conditions.
- Existing policies may limit efficient response to climate change. Changes in policies such as crop subsidy schemes, land tenure systems, water pricing and allocation, and international trade barriers could increase the adaptive capability of agriculture.

Many of these strategies will be beneficial regardless of how or whether climate changes. Goals and objectives among countries and farmers vary considerably. Current climate conditions and likely future climates also vary. Building the capability to detect change and evaluate possible responses is fundamental to successful adaptation.

13.10. Research Needs

The continuing uncertainty in projections suggests three critical, high-priority research needs:

- Development and broad application of integrated agricultural modeling efforts and modeling approaches particularly applicable at the regional scale, including increased attention to validation, testing, and comparison of alternative approaches. Climate effects on soils and plant pests, consideration of other environmental changes, and adaptation options and economic responses should be an integrated part of the models rather than treated on an *ad hoc* basis or as a separate modeling exercise. Inclusion of these multiple, joint effects may significantly change our “mean” estimate of impact, and more careful attention to scale and validation should help to reduce the range of estimates for specific regions and countries across different methodologies.
- Development of the capability to readily simulate agricultural impacts of multiple transient climate scenarios. Study of the sensitivities of agriculture to climate change and the impacts of doubled-CO₂ equilibrium scenarios has not led to the development of methods that readily can be applied to transient climate scenarios. To deal credibly with the cost of adjustment, about which there is significant uncertainty, the process of socioeconomic adjustment must be modeled to treat key dynamic issues such as how the expectations of farmers change, whether farmers can easily detect climate change against a background of high natural variability, and how current investments in equipment, education, and training may lead to a system that only slowly adjusts, or adjusts only with high cost and

significant disruption. The ability to readily simulate effects under multiple climate scenarios is necessary to quantify the range of uncertainty.

- Evaluation of the effects of variability rather than changes in the “mean” climate, and the implication of changes in variability on crop yields and markets. Extreme events have severe effects on crops, livestock, soil processes, and pests. The more serious human consequences of climate change also are likely to involve extreme events such as drought, flooding, or storms, where agricultural production is severely affected.

State-of-the-art research has begun addressing these areas, and a number of promising approaches have begun to appear in the literature or are expected soon. Most are, as yet, “demonstration” research projects, choosing limited geographic areas where data are more available and considering convenient examples for climate scenarios. Caution in drawing broader policy implications from such studies is warranted because there is little or no basis to make inferences to broader populations, to other locations, or to specific climate scenarios.

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